AN INVESTIGATION OF SOME OF THE RESISTANCE ASPECTS OF THE CATAMARAN HULL

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SUMMARY

A symmetrical hull catamaran with dimensions in line with current proposed submarine rescue vessels was designed and tested at several hull spacings in order to determine the effect of separation on resistance. A single hull was tested to assess the relative increase in resistance or interference compared to the infinite separation represented by the single hull results.

In general, it was found that the resistance decreased with increasing separations and for certain speeds and separations favorable interference was observed which made the overall resistance slightly less than twice the single hull results.

A comparison with the submarine rescue vessels, a Taylor expansion and a comparable single hull ship is made where in the case of the latter the catamaran demonstrates its superiority at speed length ratios greater than 1.2.

The effect of trim for the proposed design is also evaluated, resulting in decreased resistance with trim by the stern. A possible method employing the use of a single model to predict the resistance of a catamaran was tested with promising results.

INTRODUCTION

The catamaran may be defined as a float or sailing craft formed of logs tied side by side some distance apart or as a vessel, usually propelled by sail, formed of two hulls or floats held side by side by a frame above them. This thesis will be concerned with the second definition modified in that the catamaran will be powered and the full sized ship will be 200 ft. long.

The catamaran was probably first used by the Polynesians in their fishing voyages and later in their voyages to various islands for settlement. As the number of people carried and the length of the voyages increased, so did the size of the catamaran until it reached a length of around eighty or a hundred feet. (35)[1]

The next principle development in the use of the large catamaran, as far as the authors are able to ascertain, was the construction of two large English channel steamers, the <u>Castalia</u> and the <u>Calais Douvres</u>. Particulars of these vessels are given in Table I. (16)

More recently, catamaran types have been built by the Japanese for use as tourist vessels, lake excursion boats, and ferries. These are illustrated by Nippon Kokan's <u>Sea Palace</u> (tourist vessel), <u>King Pair</u> & <u>Queen Pair</u> (ferries),

[1]Numbers in parentheses refer to references listed in the Bibliography.

TABLE I

CATAMARAN SHIPS - BUILT OR UNDER CONSTRUCTION

SHIP AND SERVICE	LBP(ft)	B_{OA}(ft)	B_{Hull}(ft)	H(ft)	Δ_{FL}/hull (tons)	C_B	C_p	C_x	$\Delta/(.01L)^3$ /per hull	B/H	L/B	L/H	V_{des} (Kts)	$V/\sqrt{L}$	Q/B	Q/L	Remarks
SEA PALACE (Tourist Vessel-Nippon Kokan)	124.5	42.0	11.8	8.2	205.0	0.590	0.713*	0.829*	106	1.44	10.55	15.20	14	1.25	2.56	0.242	Symmetric
KING PAIR & QUEEN PAIR (Ferries-NKK)	111.5	43.3	13.1	11.1	281.7	0.600			203	1.18	8.50	10.00	13	1.23	2.30	0.271	Symmetric
AKATSUKI, ASAAKE, ASANGI (Car Ferries-NKK)	124.5	52.5	17.35	7.7	275.0	0.572	0.649*	0.882*	142	2.25	7.18	16.20	13	1.16	2.04	0.282	Symmetric
KURAKAKE MARU, THIDAR I & II (Lake Excursion & Ferry)	72.1	38.1	10.63	6.56	92.0	0.618	0.764*	0.878*	245	1.625	6.78	11.00	10	1.18	2.56	0.380	Symmetric
OCEANOGRAPHIC RESEARCH VESSEL (John Hopkins Univ.-Geo.Meese Des.)	99.2	33.0	10.17	4.83	75.0	0.540	0.771	0.700	77	2.11	9.75	20.55	18	1.805			Asymmetric 10ft.Clear Separation
CASTALIA	290. Extreme	60.	17.	6.50				0.947							2.53	0.148	Asymmetric
CALAIS DOUVRES	300. Extreme	62.	18.25	6.625				0.951							2.40	0.146	

*Approximated from sketch

TABLE I

Akatsuki, *Asaake*, & *Asangi* (car ferries), and *Kurakake Maru* & *Thidar I* & *II* (lake excursion & ferry). See Table I. (20)

A large catamaran has also been constructed for use as an oil well drilling platform.

By virtue of its increased transverse stability (i.e., twin hulls with a large space in between) and the fact that a large increase in available deck area results from separating the two hulls, the catamaran is an obvious choice for use in oceanography where an essentially stable platform is required. A catamaran type oceanographic research vessel has been designed for Johns Hopkins University.[2]

Catamarans are also being considered for use as fishing vessels because of the above characteristics.

However, the authors interest in the subject of catamarans was mainly stimulated by the extensive testing which is being done by the United States Government at the David Taylor Model Basin on a catamaran hull form for use as an ASR (submarine rescue vessel). A small rescue submersible has been designed to descend and rescue members of a submarine crew. This submersible will be launched and recovered by a mother ship, the ASR. Designing and building this mother ship as a catamaran will allow the launching and recovery of the rescue submersible in the relatively calm

[2] The above information and that given in Table I on the Meese design was obtained during a telephone conversation with Mr. Geo. Meese on 14 July 1966.

waters between the hulls. Five models were built and tested at the David Taylor Model Basin. Of these five, one was symmetrical and the other four were asymmetrical forms. The decision by the Navy was to use the asymmetrical hull form. This decision was not based on resistance characteristics of the two types, but rather on the handling requirements for the rescue submersible. (10) (12) (13) (14)

A search of available literature revealed that very little information is available for large powered catamarans, and certainly nothing that could qualify as a systematic study of some of the possibilities for lowering hull resistance. This thesis is intended to represent a first step toward a systematic series on catamaran hulls.

As much information as was available on existing catamaran designs was collected and is tabulated herein in Tables I & II for purposes of comparison. It is hoped that this information, along with the data from this thesis, will assist in selecting future designs to continue the study in the form of a related series.

The current interest of the United States Navy in the catamaran for its new ASR may be illustrated by a quote from an abstract of a paper by Meier, H. A., "Preliminary Design of a Catamaran Submarine Rescue Ship (ASR)":

> The submarine rescue ship has as its primary mission the handling and support of a new design rescue submersible. The catamaran appeared to be suited ideally to handling large heavy weights and hence was investigated as a suitable configuration for this ship. It was found

that, in addition to simplifying the hoisting problem, the catamaran has superior low-speed maneuverability; and when compared to a single hull of approximately the same displacement, it has a 40% increase in deck area. These advantages were felt to justify the extensive model testing necessary to insure a structurally and hydrodynamically sound final design. Both symmetrical and asymmetrical hulls with varying hull spacing were tested resulting in the selection of the asymmetrical hulls with the spacing selected solely on the basis of handling requirements. Resistance was found to be insensitive to hull spacing over the practical range of spacing... (18)

SELECTION OF MODEL DIMENSIONS AND COEFFICIENTS

To bypass the preliminary design process and still end up with a hull form is analogous to satisfying a set of boundary conditions, writing a potential function, and trying to find an application for this function. Arriving at the dimensions and coefficients for this catamaran, herein referred to as WC-1, was a similar but a more guided process. The boundary conditions or limits were the successfull catamarans that have been built, plus the various proposed hull forms represented by models that have been tested. These are tabulated in Tables I and II, respectively.

In the selection of the hull form more weight was attributed to ships that had been built and models that evolved from a documented preliminary design process as compared to the more theoretical hull forms, with the hope that WC-1 would be functional as a seagoing vessel.

Selection of the dimensions and coefficients for this design were dictated by the anticipated service of the vessel; namely, a submarine rescue, oceanographic research, and possibly a fishing vessel. The hull form as developed was guided by current naval architecture and hydrodynamic principles. (31) (32) (27) It is felt by the authors that the same hydrodynamic principles used in the development of a single hull form are applicable to the catamaran.

The considerations for the selection of the major hull parameters are as follows:

1. Symmetric or Asymmetric Hulls

To date the largest amount of experimentation on large displacement type catamarans has been on the symmetric hull form, (4) (19) (29)(36) (i.e., symmetry about individual hull axis). The majority of catamarans built and in service are also of the symmetric type. The resistance characteristics of the symmetric type are in general superior at low speeds and inferior at higher speeds as indicated in Fig. 6 for the David Taylor Model Basin ASRs,,the crossing point being $V/\sqrt{L} = 1.1$ The reason for this is that the asymmetrical hull form when properly designed lends itself to better cancellation of the interaction wave and keeps the relative heights of the inside and outside wave on the hull very close. (14)

As the aforementioned crossover point cannot be clearly defined in terms of speed length ratio it was decided to investigate the symmetric hull form for the following reasons:

a) Conventional hull design techniques are more applicable.

b) The advantage of towing a single hull model and thus being able to evaluate the interference effect by comparing various hull separations to twice the single hull, the latter being representative of the infinite separation case in which there is no interference effect.

c) The symmetric hull lends itself to a smaller waterline entrance angle which should lead to lower resistance values.

2. Displacement-Length Ratio

Numerical values of the $\Delta/(.01L)^3$ ratios of catamarans that have been built or under construction fall into the 150-160 range. (See Table I) A similar result was obtained for proposed designs (See Table II). By excluding $\Delta/(.01L)^3$ below 50 or above 300 a $\Delta/(.01L)^3 = 175$ was selected as it is near the numerical average of Tables I and II and is representative of the first four Submarine Rescue Vessels which initially stimulated this investigation. (10) (11) (12) (13)

It was also anticipated that with $\Delta/(.01L)^3 = 175$ a reasonable Taylor power prediction could be made by extrapolating R_T/Δ values to the lower beam-draft ratios and attempting to optimize the prismatic coefficient. This same technique was used by the Naval Ship Systems Command for their symmetric hull ASR.

3. Beam-Draft Ratio

Since the stability of the catamaran is more dependent on hull separation and not beam, a certain amount of latitude is afforded in the selection of the beam, which in turn gives a wide range of beam-draft ratios.

The range of B/H for the designs tabulated (Tables I & II) is from 0.91 to 2.95. As draft was a limitation in some of these designs a numerical average would not be justified.

TABLE II

PROPOSED CATAMARAN SHIPS AND MODELS

SHIP AND SERVICE	LBP(ft)	B_{OA}(ft)	B_{Hull}(ft)	H(ft)	Δ_{FL}/hull (tons)	C_B	C_P	C_X	$\Delta/(.01L)^3$ /per hull	B/H	L/B	L/H	(kts) $V_{des.}$	$V/\sqrt{L}$	S/B	S/L	Remarks
ASR (Mod. 5060,5061)	210	86	24	18	1397	0.539	0.549	0.982	150.85	1.330	8.750	11.66	16	1.10	2.58	.2955	5060 Symmetric 5061 Asymmetric
ASR (Mod. 5093)	210	88	26	19	1600	0.539	0.551	0.979	172.77	1.368	8.077	11.05	16	1.10	2.38	.2955	Asymmetric
ASR (Mod. 5094)	210	86.06	26.03	17.9	1600	0.585	0.601	0.973	185.18	1.450	7.880	11.70	16	1.117	2.31	.2860	Selected Des. Asymmetric
ASR (Mod. 5116)	230	86	26	19	1764	0.538	0.547	0.983	140.9	1.368	8.931		15	0.980	2.31	.2610	Asymmetric
Catamaran Ferry (Atlantic Hydrofoil)	153		10.1	3.42	62.5	0.414	0.788	0.525	17.4	2.950	15.15	44.80					Asymmetric
Mandel Paper (1962 SNAME) (3 Displ. Cats.)	327 412 519	69 87 109.6	23 29 36.5	7.7 9.7 12.2	1000 2000 4000	0.605 0.605 0.605			28.6 28.6 28.6	2.950 2.950 2.950	14.20 14.20 14.20	42.50 42.50 42.50			2.00 2.00 2.00	.1408 .1408 .1408	
H-2 Catamaran (Cyrus Hamlin)	136	48	12	10.5	250	0.510			100	1.040	11.33	12.90			3.00	.2650	
Schimke-Puchstein Paper (German)																	
Mod. U-50	10.06		1.55	1.42	.324	0.500	0.525	0.954	316	1.090	6.52	7.12					U-Form
Mod. U-55	10.06		1.55	1.42	.355	0.550	0.577	0.953	348	1.087	6.52	7.12					U-Form
Mod. S-59	10.06		1.31	1.43	.324	0.589	0.616	0.957	316	0.915	7.71	7.07					S-Form
Mod. S-65	10.06		1.31	1.44	.357	0.654	0.682	0.959	350	0.910	7.71	7.00					S-Form
Mod. S-71	10.06		1.31	1.44	.386	0.706	0.733	0.963	379	0.910	7.71	7.00					S-Form

TABLE II

In order to take advantage of the flexibility in selection, a beam-draft ratio of 1.5 was selected, giving a narrow beam which would reduce the amount of wavemaking and improve the overall resistance. On the other hand, one might also argue that a larger B/H value would give less wetted surface.

The single hull stability of the model was considered in view of the fact that it would be tested by itself in order to predict the infinite separation case by doubling the results and thus serve as a datum for comparison.

4. Length and Blockage

The minimum acceptable length for reproducible model results at the Robinson Model Basin for non-planing type vessels is four feet. With this limitation the $\Delta/(.01L)^3$ value of 175 per hull is equivalent to a single hull value of 350. In this area there is a definite blockage effect owing to the dimensions of the towing tank. The blockage effect expressed as a percentage of tank cross-section was calculated on the basis of one hull in 1/2 the tank divided vertically. Using a rough figure of 1/2 per cent as the upper limit for displacement type hulls and the 5' x 5', 1/2 cross section of the tank, the upper limit for maximum section area of the model without measurable interference is 18 in^2.

This would be impossible to obtain having set $\Delta/(.01L)^3 = 175$ and L=4 ft. Therefore it was decided to calculate a blockage effect and eliminate as much as possible the turbulence stimulation problems associated with smaller models.

5. Maximum Section Coefficient

Investigation of the wave profiles on the David Taylor Model Basin ASR'S (10)(11)(12)(13)(14) indicates that there is a considerable amount of three-dimensional flow in the region of the maximum section at and above design speed. This is probably due in part to the large interference wave system built up between the two hulls which creates a pressure differential between the inside and outside of each hull, and increases the transverse flow.

It was felt by the authors that flow conditions could be somewhat improved by using a lower maximum section coefficient than the above designs employed. In light of this, a maximum section coefficient of 0.90 was incorporated in the design.

At first the 0.90 value may not seem particularly fine. However, when incorporated in a body plan (Fig.2) with a low beam draft ratio and wall sides extending below the design waterline, the resulting section appears somewhat finer than one generally associates with $C_x=0.90$.

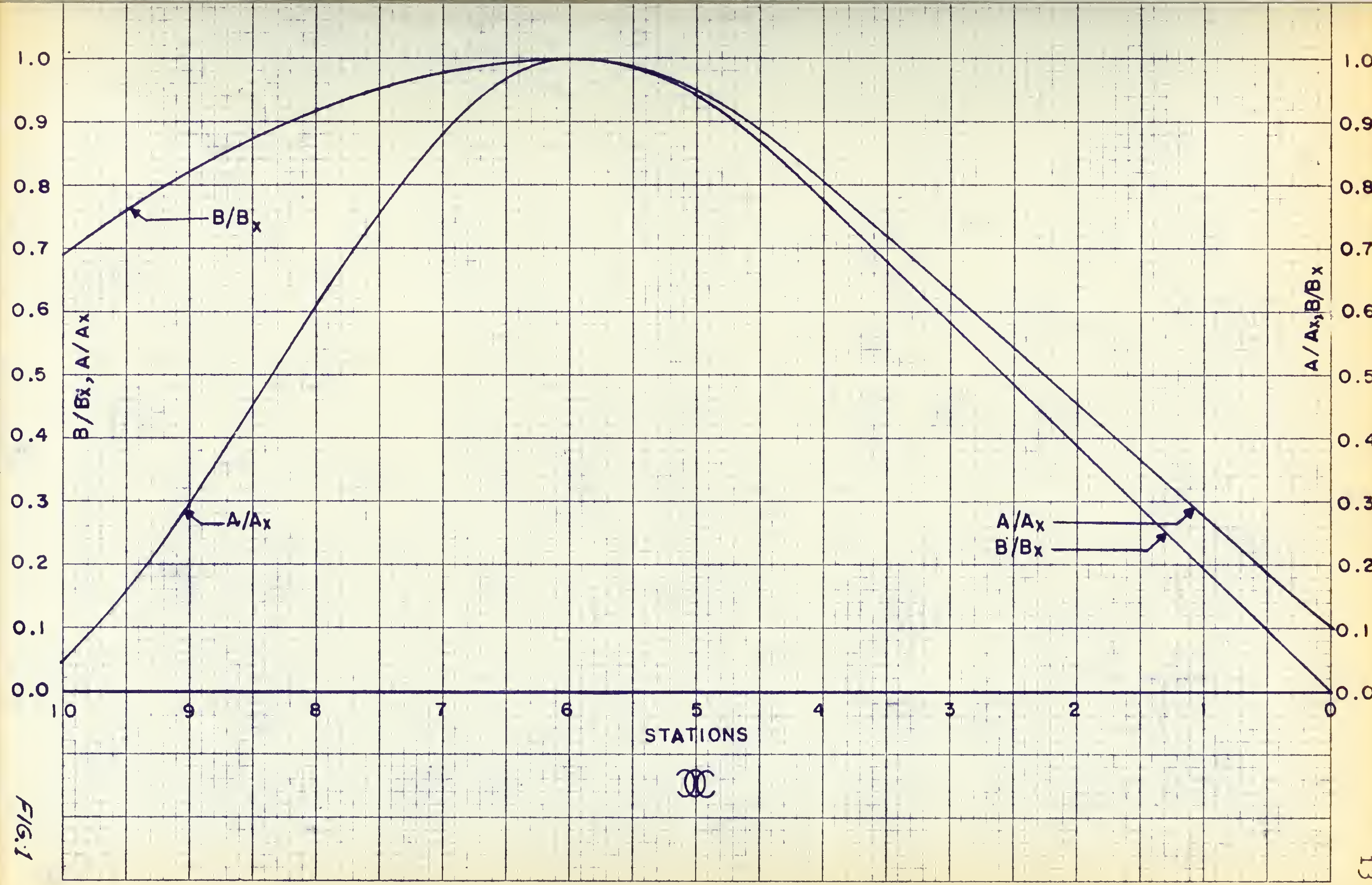
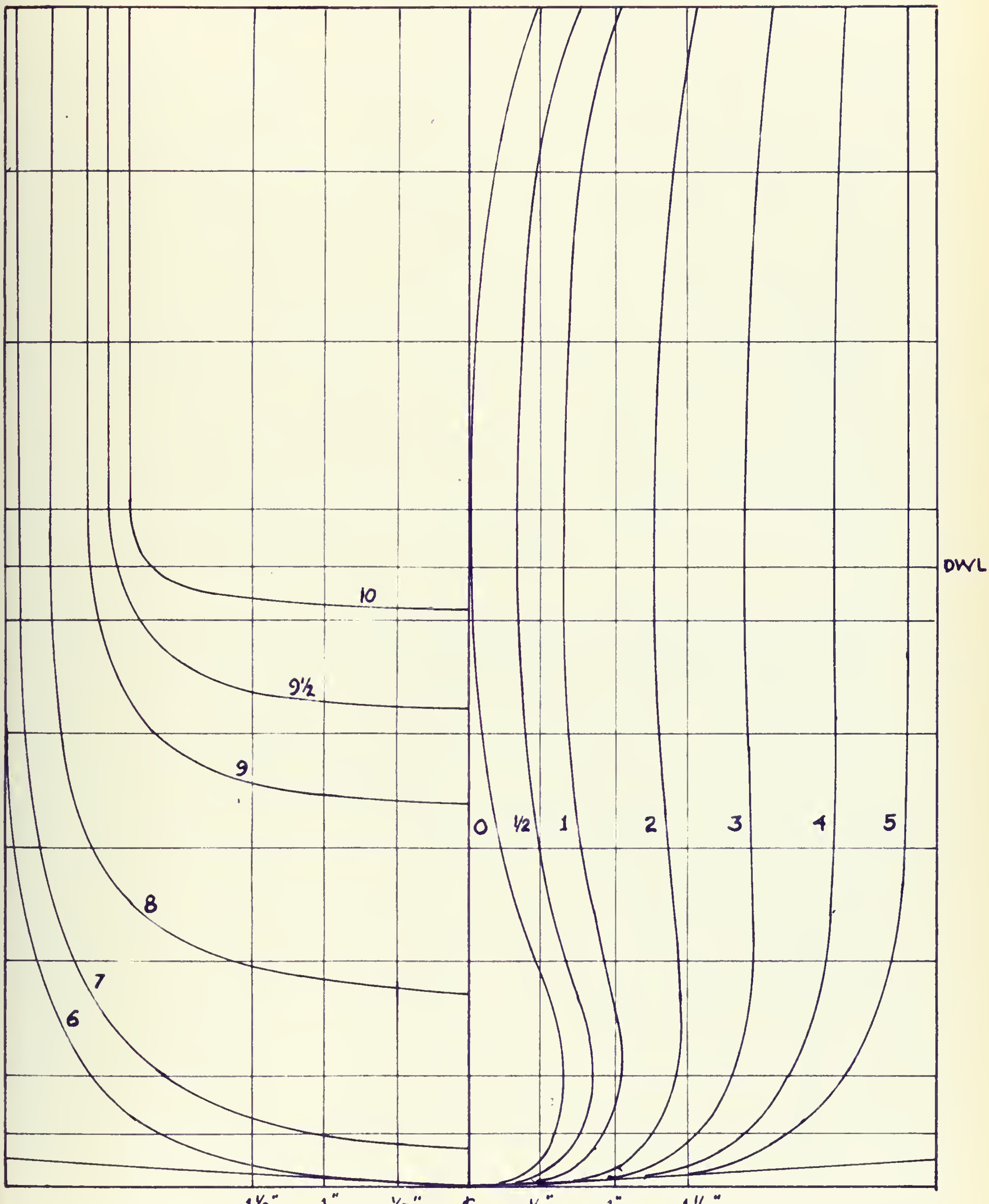

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
B/Bx, A/Ax
A/Ax, B/Bx
B/Bx
A/Ax
A/Ax
B/Bx
10
9
8
7
6
5
4
3
2
0
STATIONS

FIG. 1

FIG-1



WC-1

BODY PLAN - MODEL SCALE

FIG. 2

6. Prismatic Coefficient

An attempt was made to optimize the prismatic coefficient based on a Taylor prediction. This method cannot really be justified as all values tabulated were at the high $\Delta/(.01L)^3$ values of this series and were also extrapolated linearly to a beam-draft ratio of 1.5. The results of this calculation showed an optimum $C_p = .61$. Consultation with the high $\Delta/(.01L)^3$ values for the Webb Trawler Series showed a similar result. (23)(24) In light of these two comparisons and the David Taylor Model Basin trend towards a higher prismatic coefficient (See Table II), a value of .60 was selected as being representative.

7. Position of the Longitudinal Center of Buoyancy (LCB)

For the design speed length ratio of WC-1 Todd (34) recommends the position of the LCB to be from 1 to 2% aft of amidships. The initial position of the LCB was not fixed to any specific number except in the case of a preliminary section area curve where it was placed at 1.5% aft of amidships in order to insure that it would be in the 1% - 2% range. The resulting integration of the completed lines plan showed the LCB to be at 1.2% aft of midships. This value was considered acceptable as it was planned to trim the

model by the stern to evaluate the effect of trim. Trim by the stern would also move the LCB aft and would give some measure as to its effect on resistance.

8. Bulbous Bow

It has been demonstrated in many cases that a bulbous bow improves the resistance qualities of ships at high speeds. As this vessel is considered a high speed vessel having a design $V/\sqrt{L} = 1.25$, it was decided to incorporate a bulb in the design. See Fig. 2.

The size of the bulb was arbitrarily set at 10% of maximum section area (Fig. 1), which, in general, is considered a fairly large size. The appearance of the bulb in the body plan (Fig. 2) is deceiving, as far as size is concerned, for the same reasons mentioned in the discussion of maximum section coefficient.

Another good argument for the incorporation of a bulb is its effect on interference. It is generally accepted that interference in most cases increases resistance and since it is a wavemaking phenomenon, any reduction in wavemaking would reduce interference.

9. Transom Stern

The transom stern, like the bulbous bow, has a favorable influence on the resistance of high speed ships as it allows for clear separation of the flow

away from the stern and thus increases the apparent waterline length of the vessel. Using methods outlined by St. Denis (32), the transom area recommended was 10% of maximum section area. This value was considered large and was reduced to 5% for the following reasons:

a) This method of predicting transom size is based on a small series of destroyer sterns and has not been updated since 1939.

b) The 10% figure, when applied to ships with larger beam-draft ratios may be feasible, but for a narrow beamed ship the resulting area would have an increased effect on the transom immersion.

Having decided on the 5% transom area, the immersion of the transom was dictated by the beam aft as the section at the after perpendicular is almost rectangular with rounded corners (See Fig. 2). This transom shape could be considered a matter of style and could have just as easily incorporated a knuckle which might, with the fore and aft position of the knuckle line, improve flow conditions in this area.

10. Lines Plan

Having established a sectional area curve (Fig. 1) incorporating the coefficients and dimensions previously discussed, the lines were developed (Figs. 2 & 3) using principles set forth by Todd (34). As the waterplane inertia about the single hull axis has little

effect on the stability of the catamaran there was no limitation in this regard and the load waterline could be made as fine as possible.

In the speed range considered Todd recommends straight waterlines forward with a half entrance angle ($\frac{1}{2}\alpha E$) of 9°. With the established beam a straight waterline was used up to station 4 with a half entrance angle of 8°. This line was then faired with a slight shoulder to its maximum value at station 6. A B/B_X value of .70 for the transom was considered reasonable and thus determined the after fairing point to which the LWL was drawn.

For this speed range it is desirable to have straight buttocks aft (34). This, in conjunction with the sectional area curve and load waterline curve, positioned the start of the cutaway deadwood at about station 7. This was originally drawn as a straight line on the profile, which essentially determined the draft at the after stations. Knowing the beam, draft and area at each station a compatability curve, which is the ratio of section area to the product of beam and draft at that section, was drawn to serve as a check and highlight any irregularities which might need further investigation. The resulting curve indicated that the transition from section to section was reasonable in that no discontinuities were present.

The transition from the keel line in way of the cutaway deadwood at station 7 was rounded and faired which made the centerline profile appear as part of the after buttock curve family. This could have been left as a straight line if a skeg was to be fitted. Since this was not the case, rounding of the keel line eliminated the introduction of recurve at station 7, which would be the logical way to effect the transition from a full draft section to one with a skeg.

The shape of the after waterlines was dictated mainly by the straight buttocks employed. The waterlines forward were made straight in keeping with the design of the load waterline. The waterline endings forward in way of the bulb were made elliptical in shape, the size of the ellipse being determined by the bow profile and its tangency to the waterlines.

The section shapes in way of and above the load waterline were kept vertical with the exception of a small amount of flare at the bow for ease of construction and also to permit some variation in draft without greatly changing the hull shape for future experiments.

11. Hull Separation

It has been found that the resistance of a twin-hulled ship decreases with increasing hull separation

(10)(11)(12)(13)(14)(19)(4)(36). Five hull separations were decided upon, namely, Q = 12", 15", 18", 21", 24", where Q is defined as the distance measured transversely from centerline to centerline between hulls as used by Eggers (4) and Schimke & Puchstein (29). These separations cover and, in some cases, exceed the ranges previously investigated. These will be non-dimensionalized in terms of length and beam as Q/L and Q/B, respectively, where B refers to the beam of a single hull. Both these non-dimensional forms appear in the literature (4)(19) and each has its own merits as to physical interpretation.

When separation is related to beam one can think of it as a nozzle or venturi phenomenon. If expressed in terms of length and assuming a 20° Kelvin wave pattern (where the angle of the wave system is 20° relative to the longitudinal axis of the body) the number of reflections or interactions of waves between the hulls increases with decreasing Q/L values.

The aforementioned coefficients and dimensions are summarized in Table III.

TABLE III

SUMMARY OF MODEL AND SHIP CHARACTERISTICS

Note: All dimensions and coefficients for one hull.

	WC-1	200 ft. SHIP
LWL	4 ft.	200 ft.
LBP	4 ft.	200 ft.
Beam/hull	0.534 ft.	26.712 ft.
Draft	0.340 ft.	17.000 ft.
Displacement/Hull	24.37 lbs FW @ 80°F	1400 tons SW @ 59°F
Wetted Surface	3.417 ft^2	8523 ft^2
Beam-Draft Ratio	1.570	1.57
Displacement-length Ratio/Hull	175	175
Block Coefficient	0.539	0.539
Prismatic Coefficient	0.598	0.598
Maximum Section Coefficient	0.900	0.900
Waterplane Coefficient	0.691	0.691
LCB	1.175% of LWL aft of ⊗	1.175% of LWL aft of ⊗
KB	0.191 ft.	9.5701 ft.
Q	Distance from centerline to centerline	
Bulb Size	10% of A_X	10% of A_X

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Bulb Size	10% of A_x	10% of A_x

MODEL CONSTRUCTION

Both hulls were constructed from lifts of clear sugar pine of approximately 3/4 inch thickness below the design water line and 1 3/8 inch thickness above. Half-breadths were taken from the body plan and the water lines were drawn on the appropriate lifts. The lifts were cut slightly oversize to insure that adequate material was available for final finishing of the models. The interior of the lifts with the exception of the bottom was removed to maintain an approximate 3/4 inch hull thickness throughout. This is thinner than most of the models examined and was considered necessary to facilitate a light model and large, low ballast weights to insure adequate stability for the single hull tests. Additional material was left at the bow, stern and amidships to facilitate doweling and to support the cross structure deck fittings. The lifts were placed in appropriate order on top of one another, aligned on the dowels, glued with Weldwood glue and left for 24 hours in a gluing press.

Templates were constructed of three-ply illustration board for all stations, half-stations at the ends, bow and stern profiles and waterlines in way of bulbous bow. Centerlines and station locations were marked on the models. Edges of the lifts were cut away until a relatively fair surface was obtained; templates, with centerline, waterlines and deckline marked thereon, were then used at appropriate stations

and at the bow and stern to bring the model nearly to the desired shape. Special planes, gouges, files, and chisels were used during this phase of construction. With the models now slightly over sized, sandpaper of varying degrees of coarseness was used until the templates fitted accurately and until a fair surface was obtained in between station locations. Visual sighting and battens were employed to assist in the fairing process.

Five coats of spar varnish were used in finishing the models. After application of the second coat, conventional sandpaper of increasing fineness and very fine steel wool was used between coats to achieve a highly smooth surface. Two coats of varnish were applied to the interior of the models to seal against moisture.

Supporting brackets for the cross structure were constructed of aluminum and mounted on the foredeck and slightly aft of amidship. (See photograph for details) The cross structure consisted of two 1 1/4 x 1 1/4 x 30" aluminum angles which could slide and lock in the deck brackets, thus facilitating adjustment of the distance between hulls. At the center of the forward aluminum angle a towing plate was mounted. Similarly, on the after angle an accelerating strut bracket was fitted. For the single hull test available towing and accelerating strut brackets were mounted forward and aft of amidships respectively.

Before testing, pins were installed forward to provide turbulence stimulation as noted under model testing procedure.

MODEL TESTING PROCEDURE

The model was tested for the following hull separations (Q - which is the distance from centerline to centerline); 12", 15", 18", 21", 24", and infinite spacing. These separations correspond to non-dimensionalized separations of Q/B equal to: 1.87, 2.34, 2.81, 3.26, 3.74, and infinite, respectively. The infinite separation was accomplished by testing of a single hull and doubling the results for comparison.

The model was towed at its design displacement in fresh water at 80°F. All testing was performed with zero list and trim. The length of the towing run was 35 feet. The towing point was located approximately 2 5/8 inches above the tank water level with the exception of the single hull test in which the height was 1 5/8 inches above the tank water level.

For all testing the small dynamometer was used with the heavy spring in the upper position for pan weights greater than one-half pound and the light spring at the lower position for pan weights less than one-half pound.

Longitudinal travel of the model was limited by an accelerating strut bracket mounted on the after cross-structure slightly aft of station five. For the single hull test a standard accelerating strut bracket was fitted aft of station five.

The mounting of the towing bracket was made adjustable by a combination of nuts and long machine screws. For each speed adjustments were made to the bracket to counteract any yaw moment and thus keep the accelerating strut from rubbing on the side of the bracket. To alleviate this repeated adjustment an additional guide was placed below the accelerating bracket and a roller installed on the lower end of the accelerating strut to restrain the transverse motion in the event of directional instability.

Turbulence stimulation was in accordance with standard procedures used at Webb Institute (22) (23) (25). The stimulators were 0.125 inch diameter by 0.035 inch high brass rounds drilled and countersunk to receive a fastening pin. These stimulators were placed on 1/4 inch centers on a line subtended by a transverse vertical plane located 4 inches aft of the forward perpendicular (See Fig. 4). To check the effectiveness of these stimulators an alternate arrangement of 0.125 inch diameter by 0.035 inch high brass rounds and 0.25 inch diameter by 0.0625 inch high brass rounds on 3/8 inch centers on the same line as above was used on the 15 inch separation. The results demonstrated that the original stimulator arrangement was satisfactory (See Fig.B-2).

Other steps taken to insure adequate stimulation were: 1) a water temperature of 80°F was maintained in the towing tank; 2) a time interval of two minutes between runs was used for tests, with a constant reverse speed of the model; 3) runs

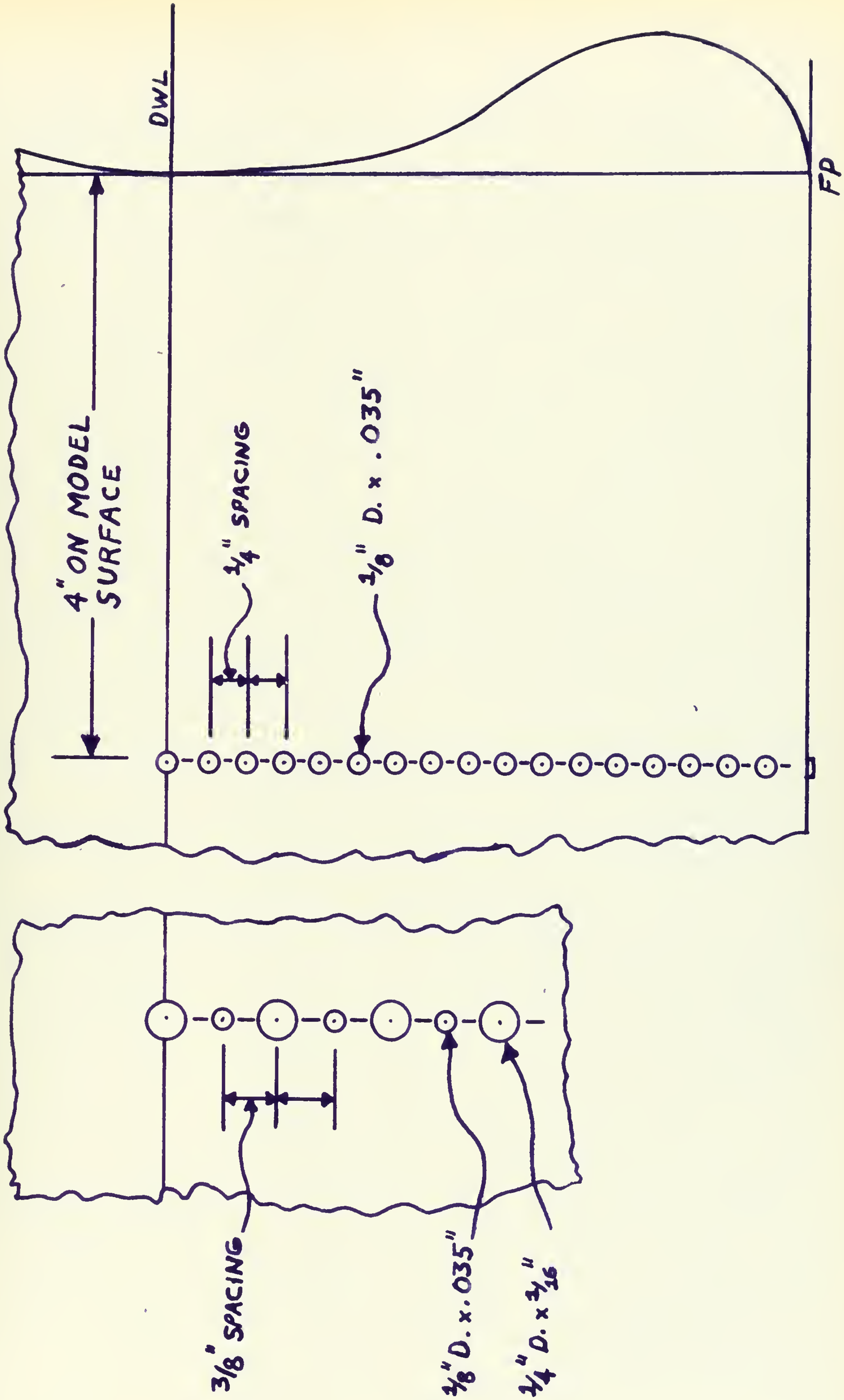

DWL
FP
4" ON MODEL SURFACE
1/4" SPACING
1/8" D. x .035"
3/8" SPACING
1/8" D. x .035"
1/4" D. x 1/16"

FIG. 4

were alternated between the high and low speed ranges.

Blockage effects were taken into consideration and correction factors were calculated as in Appendix D.

RESULTS

Model resistance tests were conducted for five hull separations (Q = distance from centerline to centerline) as well as for a single hull at constant displacement and zero trim. The model and full scale separations used as well as their corresponding non-dimensional values with respect to length and beam are as follows:

Q_{model}(inches)	Q_{ship}(feet)	Q/L	Q/B
12"	50'	.2500	1.87
15"	62.5'	.3125	2.34
18"	75'	.3750	2.81
21"	87.5'	.4375	3.26
24"	100'	.5000	3.74
Single Hull			

The resulting R_t/v^2 curves for the model tests are presented in Appendix B, Figures B-1 through B-6. These results, with the exception of the single hull, were corrected for blockage as described in Appendix D and expanded using the ITTC Friction Line, with $\Delta C_f = .004$, to 200 ft. full size. (See Appendix C for sample calculation)

The single hull case, which is considered a catamaran with infinite separation, was expanded in a similar manner without a blockage correction and using the total wetted surface of two hulls, which is essentially doubling the result.

The resulting EHP values and curves for a 200 ft., 2800 ton, catamaran for speeds from 8 to 20 knots are given

in Table IV and Figure 5. Figure 5 gives EHP values for the six separations tested with Table IV showing EHP values and variation with percentage increase in separation using Q/L = .250 as a reference separation.

From these results it can be generalized that as separation is increased, horsepower decreases, as was also found by Hankley (10), Yokoo and Tasaki (36), Michel (19), Eggers (4), Schimke and Puchstein (29), and Alexander and Byer (1).

For comparison with other ships a plot of C vs K (Fig. 6) as defined in Appendix A, is presented. For WC-1, two separations, namely Q/L = ∞ and Q/L = .3125, the latter separation corresponding to David Taylor Model Basin Model 5060 which is a symmetrical hull form for a submarine rescue vessel with comparable dimensions to WC-1, are plotted. Values for David Taylor Model Basin Models 5060 and 5061 are also plotted, the latter being an asymmetrical hull form with the same coefficients and dimensions as Model 5060.

Two other plots are presented, one a Taylor prediction (33) based on WC-1 single hull parameters, and the other a prediction from the Webb Trawler Series (25) for a $\Delta/(.01L)^3 = 350$, $C_p = .60$ single hull ship with comparable displacement and length to the twin hulled catamaran.

At the lower speeds WC-1 is inferior to the ASR's, the trawler and the Taylor estimate. With regard to the

TABLE IV

EHP vs. PERCENT INCREASE IN SEPARATION

V (Kts.)	% increase in separation using Q/L = .250 = 1				
	0%	25%	50%	75%	100%
10	600	610	580	570	560
12	1300	1200	1150	1130	1100
14	2040	2000	1930	1910	1940
16	3260	3140	3170	3080	3020
18	7750	7150	7050	7050	6900

WC-1
EHP VS. SPEED
EXPANDED ON ITTC FRICTION LINE
ΔCf = .0004
T = 59° F. (SW)
EHP x 10^-3
SPEED (KTS)
Q/L = .250 Q/B = 1.87
Q/L = .313 Q/B = 2.34
Q/L = .375 Q/B = 2.81
Q/L = .438 Q/B = 3.28
Q/L = .500 Q/B = 3.74
Q/L = ∞ Q/B = ∞

FIG. 5

FIG-5

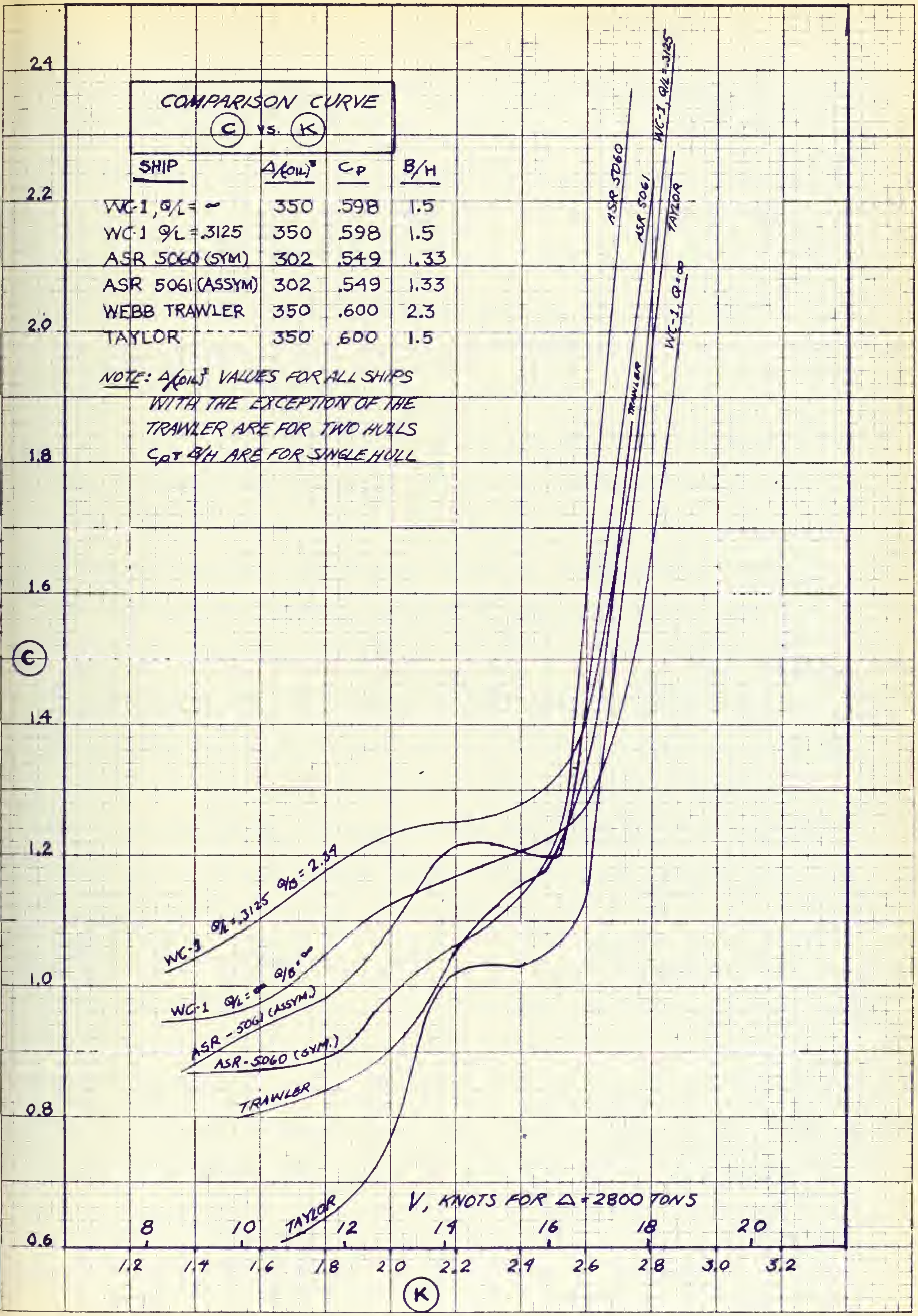

COMPARISON CURVE
C vs. K
SHIP | Δ/(0.1L)³ | C_P | B/H
WC-1, G/L = ∞ | 350 | .598 | 1.5
WC-1 G/L = .3125 | 350 | .598 | 1.5
ASR 5060 (SYM) | 302 | .549 | 1.33
ASR 5061 (ASSYM) | 302 | .549 | 1.33
WEBB TRAWLER | 350 | .600 | 2.3
TAYLOR | 350 | .600 | 1.5
NOTE: Δ/(0.1L)³ VALUES FOR ALL SHIPS WITH THE EXCEPTION OF THE TRAWLER ARE FOR TWO HULLS
C_P & B/H ARE FOR SINGLE HULL
WC-1 G/L = .3125 G/B = 2.34
WC-1 G/L = ∞ G/B = ∞
ASR-5061 (ASSYM.)
ASR-5060 (SYM.)
TRAWLER
TAYLOR
ASR 5060
ASR 5061
WC-1, G/L = .3125
TAYLOR
WC-1, G = ∞
TRAWLER
V, KNOTS FOR Δ = 2800 TONS
8
10
12
14
16
18
20
C
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
K

FIG. 6

latter, worm curves indicating inferiority or superiority to the Taylor estimate for all separations are plotted in Figure 7 to serve as a guide for a preliminary power estimate. In using these values one must consider that their validity is a function of the relative similarity of the proposed hull to WC-1 as well as the fact that the Taylor prediction represents extrapolation of the R_r/Δ values to a beam-draft ratio of 1.5.

The inferiority of WC-1 to the ASR's at low speeds can be explained by the fact that the lower prismatic coefficient of these vessels would give better performance at these speeds. The design speed of these ASR's is 16 knots which corresponds to a $V/\sqrt{L}$ value of 1.10. At 16 knots these vessels are still superior to WC-1, the percentage difference being $2\frac{1}{2}\%$ for $Q/L = \infty$ and 8% for $Q/L = .3125$. At 16.2 knots WC-1 for $Q/L = \infty$ crosses both ASR curves and remains superior, the percentage difference at 17 knots being 22% and 41% for the asymmetric and symmetric ASR's, respectively, with corresponding greater percentage differences at higher speeds.

A more realistic comparison is the relative difference between WC-1 with $Q/L = .3125$ and the ASR's, as the infinite separation case in general represents a limit of the best obtainable resistance values over the speed range. At 17 knots WC-1 with $Q/L = .3125$ is 8% better than the asymmetric ASR (Mod. 5061) and 23% better than the symmetric form (Mod. 5060).

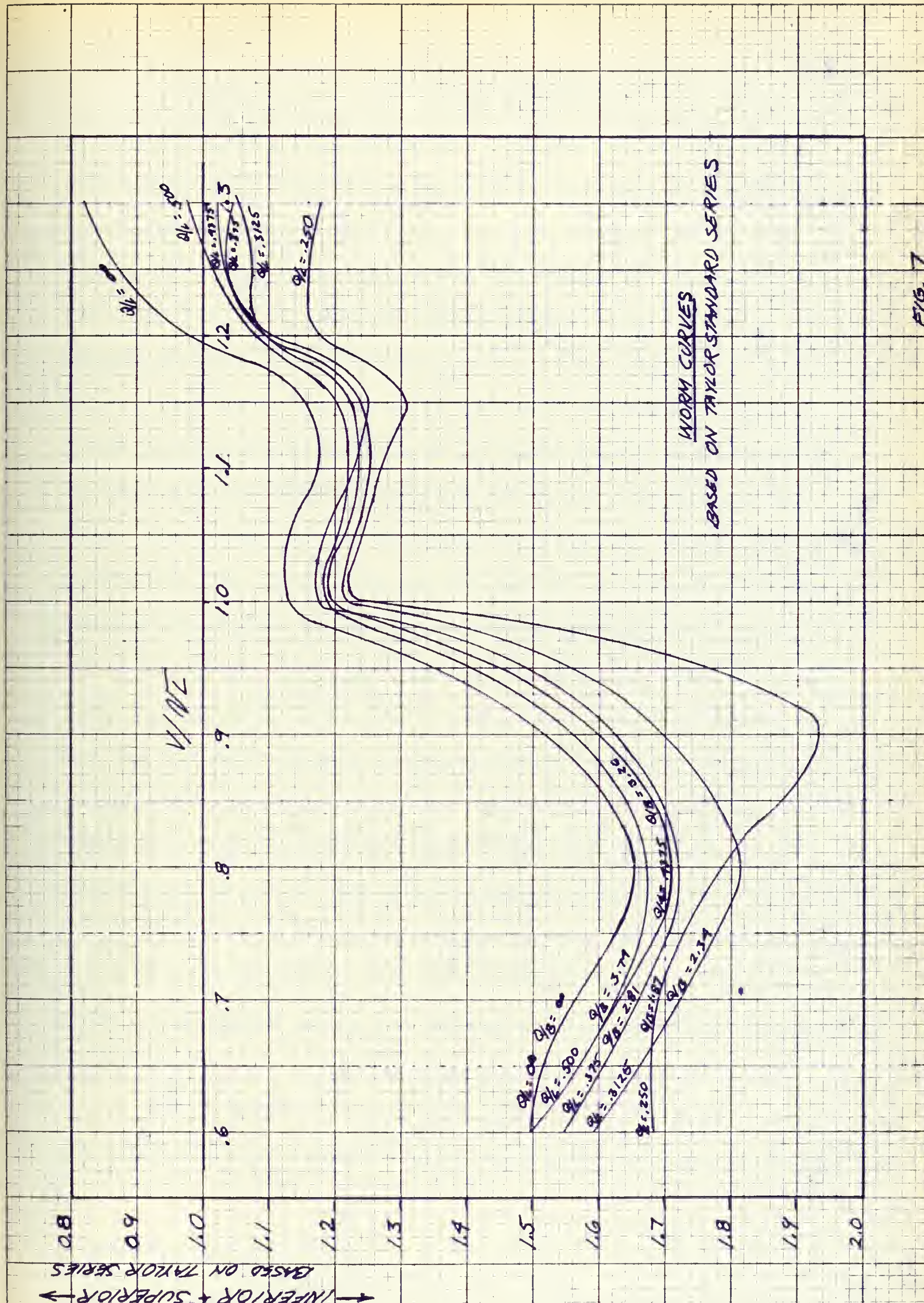

WORM CURVES
BASED ON TAYLOR STANDARD SERIES
FIG. 7
V/√L
.6
.7
.8
.9
1.0
1.1
1.2
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
← INFERIOR + SUPERIOR →
BASED ON TAYLOR SERIES

FIG. 7

The superior performance of WC-1 over the ASR's at higher speeds reinforces the findings of Michel (19), who claims that catamarans should be designed for $V/\sqrt{L}$ values greater than 1.25, which is the design point for WC-1. It also demonstrates the advantage of the bulbous bow form for high speed ships as well as the use of a larger prismatic coefficient.

The Taylor estimate is the most superior of all ships plotted at speeds up to 17 knots where it is crossed by the infinite separation plot of WC-1. Comparison of these two plots, if one accepts the validity of the Taylor prediction, is noteworthy as the latter is essentially the prediction of the infinite separation resistance, which was accomplished by doubling the results of a single hull ship with a $\Delta/(.01L)^3 = 175$. The same method was used for the infinite separation resistance of WC-1. This superiority over Taylor at the higher speeds is also reflected in the worm curves (Fig. 7) in which the finite separation of $Q/L = .500$ also becomes superior at $V/\sqrt{L} = 1.27$. A further look at the worm curves shows that at the high speed end the narrower separations come close to the Taylor prediction, which makes the catamaran look more attractive at the high speed-length ratios.

The remaining comparative plot is for a single hull $\Delta/(.01L)^3 = 350$ trawler which will serve as a comparison

of a catamaran vs. a single hull ship. The trawler is superior to WC-1 at the low speeds. However, at about 16.3 knots it is surpassed by WC-1, $Q/L = \infty$, with WC-1, $Q/L = .3125$ becoming superior at 17 knots. The balance of the WC-1 separations, with the exception of the narrowest, $Q/L = .250$, would become superior within this range as can be seen on the worm curves (Fig. 7), since they fall between the two values cited. The superior performance of the trawler at the lower speeds is due in part to the inherent smaller wetted surface of a single hull ship as compared to the catamaran, which is a controlling parameter where frictional drag represents a major portion of the total resistance. At the high speed, or wavemaking, end, however, the superiority of the catamaran can be attributed to the fine lines possible with the two hulls instead of one, where subsequent reduction in wavemaking resistance offsets the increased frictional resistance which was a handicap at low speeds. On the basis of this comparison this catamaran is competitive with the single hull ship for $V/\sqrt{L}$ greater than 1.20 and preferably should be designed above this value to offset some of the disadvantages associated with the increased hull weight which would make it competitive from a payload standpoint.

The previous discussion has dealt mainly with the full scale expanded results, which in the case of EHP values

lose some of their relative significance on the scales to which they are plotted. On the other hand, the model test results, namely the R_t/v^2 curves (Figs. B-1 to B-6) for the different separations, show considerable variation with separation. These curves, which are similar in shape to those obtained by Yokoo & Tasaki (Fig. 7-Reference 34), exhibit a series of humps and hollows at certain speeds, the severity of the humps and hollows varying with separation. For purposes of this discussion photographs for the 12" and 24" separations as well as for the single hull test are presented in Appendix E. In general, the wave patterns on the outboard side of the hull follow a pattern for the three cases. At speeds of 2.4 to 2.5 ft/sec they are characterized by a bow wave which is followed by a smaller wave at station 3 due to the bulb and a trough about amidships which rises to a crest at the stern. According to Taylor (33) this crest at the stern represents a hollow on the resistance curve which is evident in Figures B-1, B-5 and B-6, the depth of the hollow being relatively greater for the narrower separation. A similar condition is also evident at about 3.6 to 3.7 ft/sec for the three cases cited. At about 3.1 to 3.2 ft/sec the second wave due to the bulb is moving aft and flattening out making the trough at amidships deeper and reducing the height of the crest at the stern. This is characterized by a hump in the R_t/v^2 curves at this

speed range. At 3.5 to 3.7 ft/sec the characteristic wave is simply a smooth curve with a crest at the bow and stern. At this point the bulb is effective and the resulting resistance values are in a hollow on the curves. For the 24" separation it is possible to see the inside wave on the hull. At the low speeds the inside and outside waves are fairly similar. However, at 3.7 ft/sec the inside crest at the stern is forward and higher than the outside crest with the corresponding troughs being deeper for the inside wave. This difference in elevation is representative of a pressure differential between the inside and outside of the hull. This pressure differential will cause some transverse flow which would increase the resistance. Studies of the inside and outside wave profiles of the ASR's show that the asymmetric hull form can be designed to keep these relative wave heights fairly equal in elevation, and in phase. (10)(14) As this difference in wave systems was not observed at the slower speed it can be interpreted as one of the controlling factors for the superior performance of the asymmetric hull forms at the higher speeds. Another advantage of this balanced wave system is that it will give more symmetric flow conditions to the propeller.

In order to evaluate the effect of separation on resistance, an interference parameter, herein defined as the ratio of the residuary resistance coefficient (C_r) for a

certain separation (Q) divided by the residuary resistance coefficient for the single hull case (C_{r_∞}), numbers greater than one indicating greater resistance or unfavorable interference relative to the infinitely spaced hulls, was calculated. The resulting plot is shown in Figure 8.

In general, all separations show an increase in resistance over the infinite separation case, the trend, as previously cited, being less interference with increasing separation. This can be seen more clearly in Figures 9 and 10, which are cross plots of Figure 8.

A minimum of interference was found between $V/\sqrt{L}$ values of 0.85 and 1.00 with the three widest separations ($Q/L = 0.500$, 0.4375, and 0.375 or $Q/B = 3.74$, 3.26, and 2.81) showing favorable interference or less resistance than the infinite separation case, although the percentage decrease in residuary resistance did not exceed 3%. For the full scale ship this corresponds to a speed of 13 to 14 knots which, if considered as a cruising speed, would make it quite attractive.

Another fact worthy of note is that for the four widest separations the area from $V/\sqrt{L} = 1.1$ to 1.2 shows a certain flattening out of the curve which, if one wishes to accept the increase in residuary resistance which ranges from 7% to 28%, could determine an operating range of from 15 to 17 knots for a 200 ft. ship. This point is the last

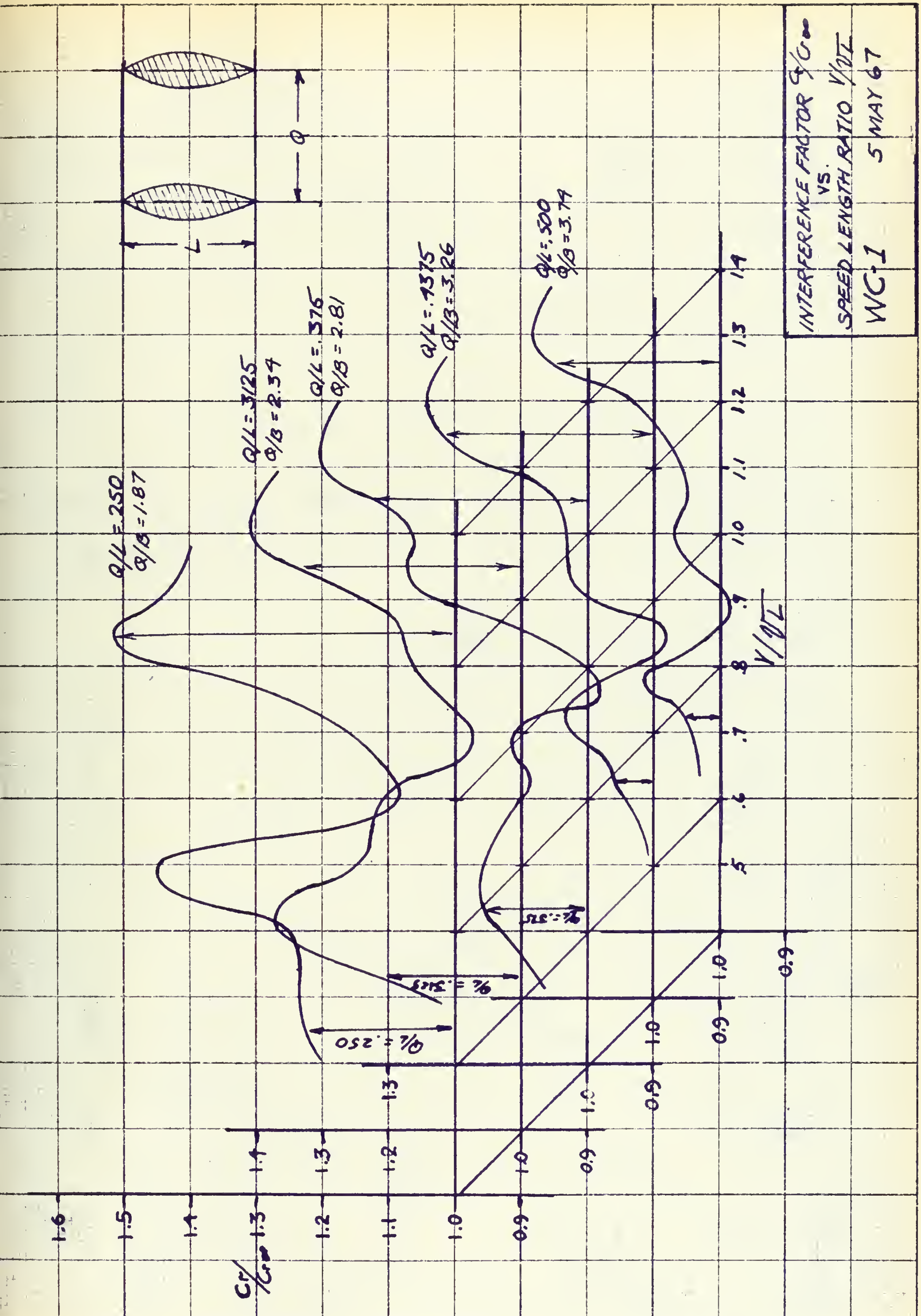


FIG 8

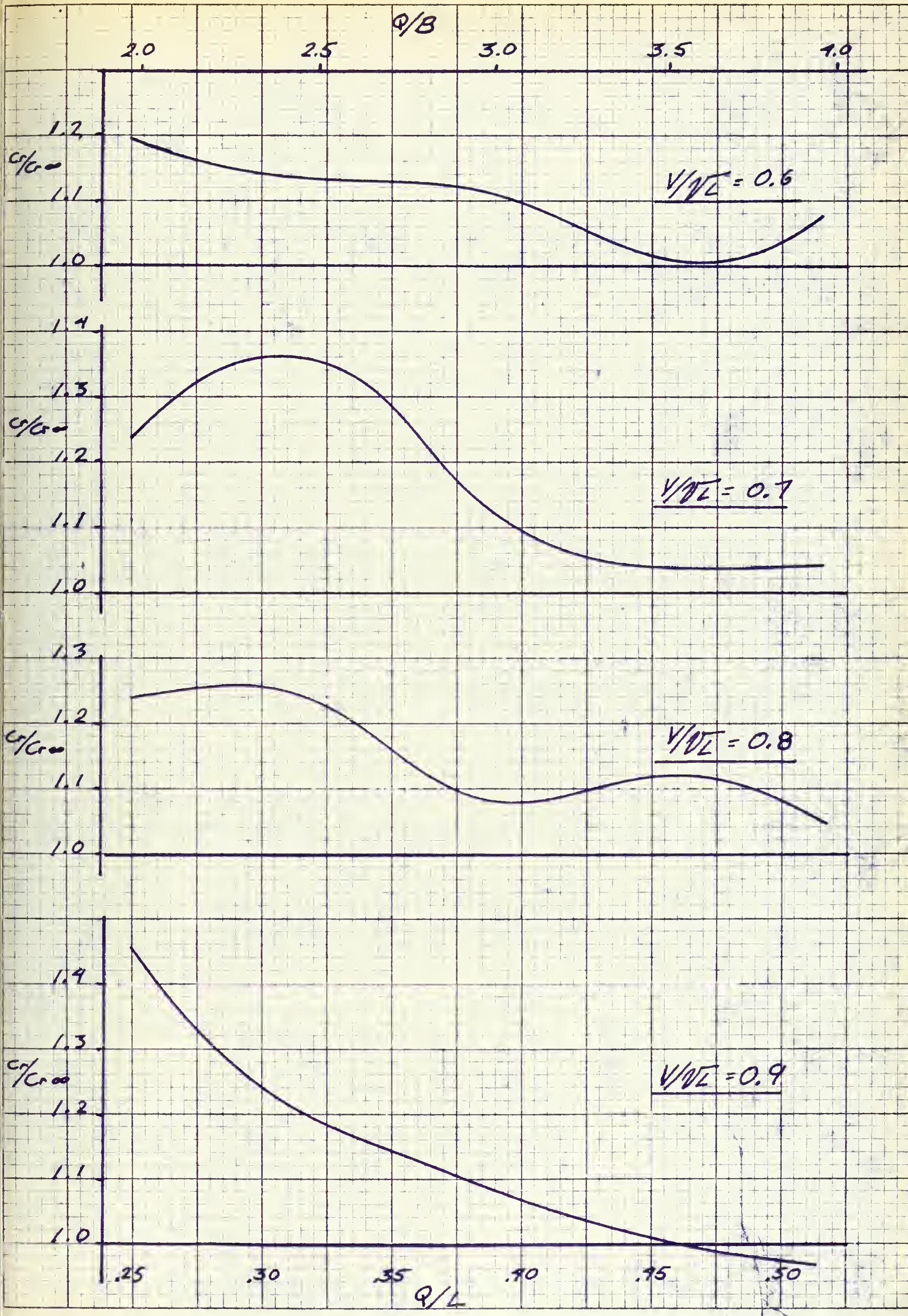
FIGURE 8

hollow shown on the R_t/v^2 curves (Fig. B-1 to B-6) which, as mentioned earlier, is where the bulb becomes effective (See photographs in Appendix E for v = 3.5 to 3.7 ft/sec).

All the separations have a maximum peak at $V/\sqrt{L}$ approximately equal to 1.30 and then indicate a decrease in residuary resistance which makes a higher speed than this look attractive. This is more in line with Yokoo & Tasaki (34) who claim that a favorable area for design is for $F = v/\sqrt{gL} = 0.4$ which corresponds to a $V/\sqrt{L} = 1.38$. This is beyond the speed range tested. However, the downward trend of the curves after $V/\sqrt{L} = 1.3$ tends to reinforce their results.

As mentioned previously the worm curves (Fig. 7) can give a preliminary power prediction based on Taylor. With similar limitations, if one has single hull residuary resistance coefficients, Figures 9 & 10 will facilitate a prediction for a catamaran with the hull separation serving as a variable.

The general trend for the interference curves and the cross plots is a decrease in C_r/C_{r_∞} with increasing separation. However, the two narrowest separations in general appear to have a greater increase in resistance especially at the low speed end where the variation with separation appears to have a transition region at about the mid-range of separations plotted as can be seen in Figure 9. As a



Q/B
2.0
2.5
3.0
3.5
4.0
1.2
1.1
1.0
Cr/Cr∞
V/√L = 0.6
1.4
1.3
1.2
1.1
1.0
Cr/Cr∞
V/√L = 0.7
1.3
1.2
1.1
1.0
Cr/Cr∞
V/√L = 0.8
1.4
1.3
1.2
1.1
1.0
Cr/Cr∞
V/√L = 0.9
.25
.30
.35
.40
.45
.50
Q/L

FIGURE 9

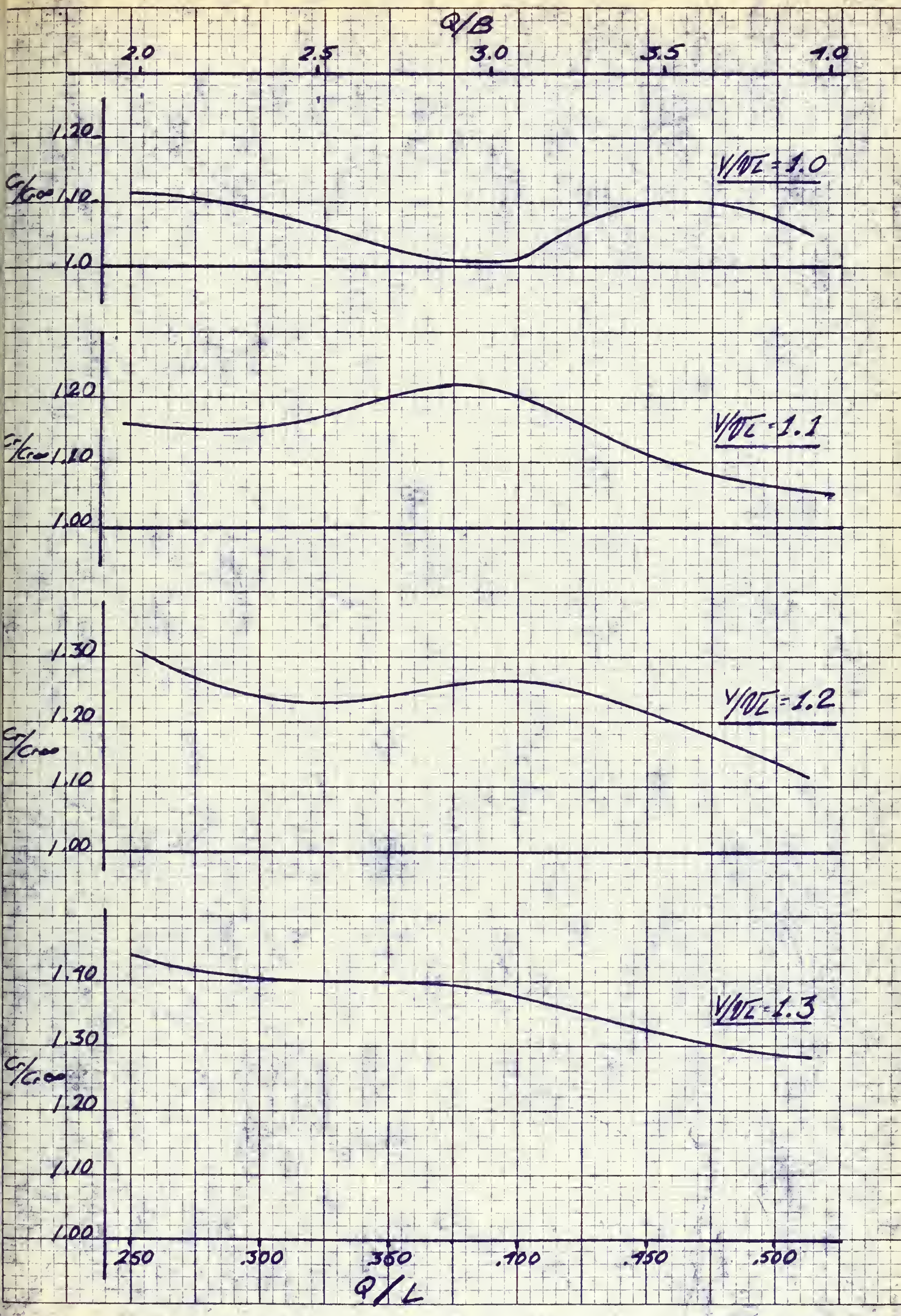
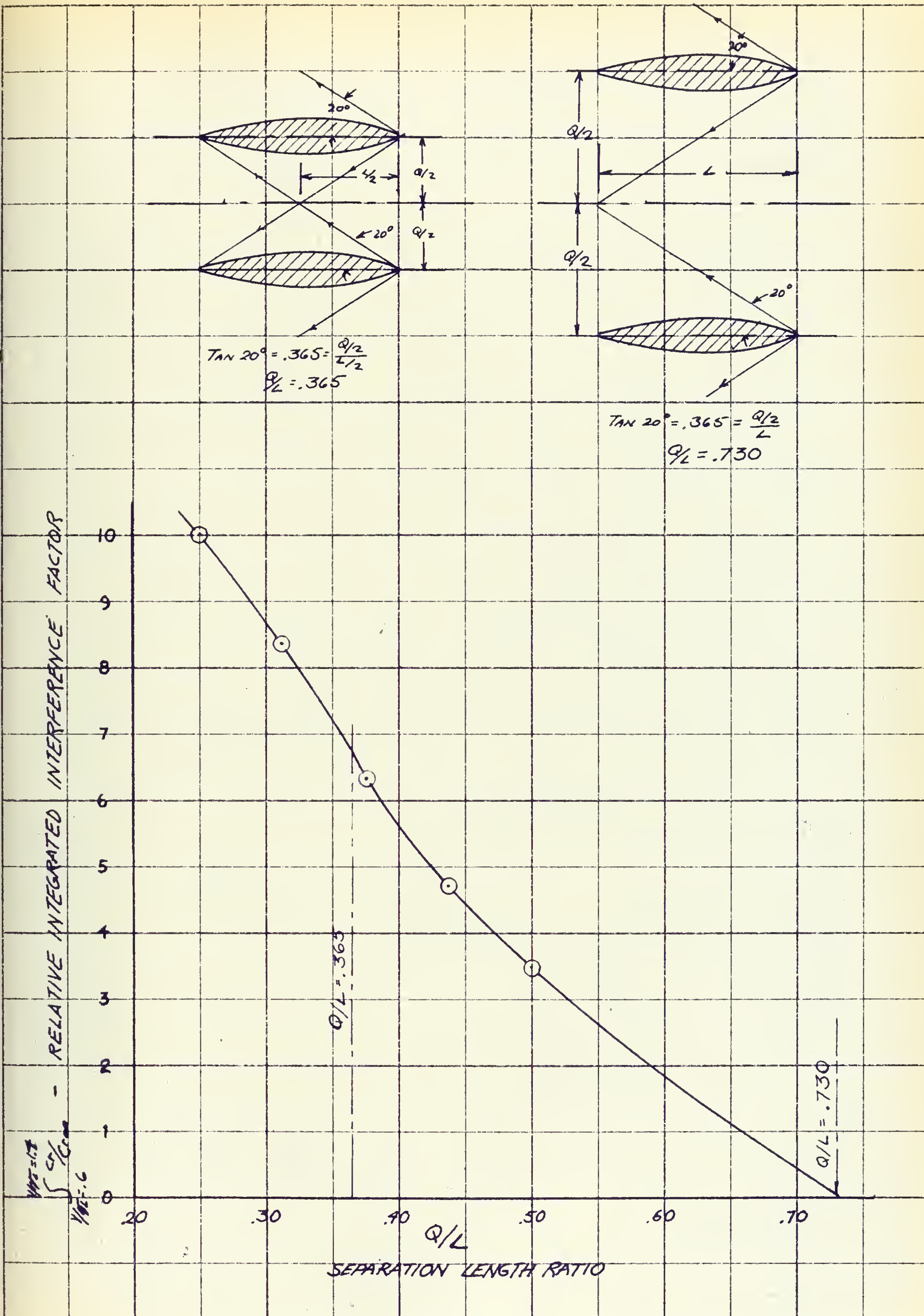

Q/B
2.0
2.5
3.0
3.5
4.0
1.20
Cr/Cr∞ 1.10
1.0
V/√L = 1.0
1.20
Cr/Cr∞ 1.10
1.00
V/√L = 1.1
1.30
1.20
Cr/Cr∞
1.10
1.00
V/√L = 1.2
1.40
1.30
Cr/Cr∞
1.20
1.10
1.00
V/√L = 1.3
.250
.300
.350
.400
.450
.500
Q/L

FIGURE 10

method of evaluating the general effects of separation the interference curves were integrated from $V/\sqrt{L} = 0.6$ to 1.4 and the values plotted in Fig. 11. The ordinate of the curve is simply a relative number based on the integration, taking the area for Q/L = .250 as equal to 10. In trying to fair this curve a hump or discontinuity was found between Q/L = .375 and Q/L = .3125. To explain this phenomenon the following theory is proposed. If one assumes a Kelvin wave pattern (which is essentially a 20° crést line with the longitudinal axis of the body), for the bow wave, the geometry is such that certain calculations can be made to determine one more point to which the curve can be extrapolated and to also locate the aforementioned discontinuity.

Assuming that the inside bow wave from each hull meets at the centerline plane between the two hulls and is reflected back to itself with the associated reflection angles related to the 20° bow wave, the point at which the reflected wave will not hit the hull will be above a Q/L = .365 as shown in Figure 11. This point is shown as a discontinuity on the integrated C_r/C_{r_∞} curve. By similar reasoning the end point or separation corresponding to a point where there should be no interference was predicted by assuming the bow waves meet at the stern. This corresponds to a Q/L value of .730 (See Fig. 11). The integrated curve was faired to a zero value at this separation.



20°
Q/2
L
L/2
TAN 20° = .365 = (Q/2)/(L/2)
Q/L = .365
TAN 20° = .365 = (Q/2)/L
Q/L = .730
RELATIVE INTEGRATED INTERFERENCE FACTOR
10
9
8
7
6
5
4
3
2
1
0
.20
.30
.40
.50
.60
.70
Q/L = .365
Q/L = .730
Q/L
SEPARATION LENGTH RATIO

FIG. 11

One might question the validity of integrating over the speed range for this evaluation, thinking that the wave changes with speed, which it does as shown in the photographs (Appendix E). However, the wave change is an amplitude and energy phenomenon, whereas, this approach uses only the directional properties of the wave, namely the 20° angle which does not change with speed.

Figure 11 can be considered as an overall performance curve vs. separation for the speed range covered. However, it should not be used to assess total percentage improvement as it only reflects the integrated value of the interference factor ($C_r/C_{r_{\infty}}$), which only considers residuary resistance. Based on this theory one can conclude that it is desirable to design a catamaran for Q/L values greater than .365 with better results being obtained as the separation-length ratio approaches .730. For large displacement vessels this may not be practical, but for the small sail and power catamarans this seems to be in line with existing designs.

In addition to the above results the effect of varying the trim by the stern was evaluated for one separation, namely, Q = 18" (Fig. B-3). This was prompted by observations during testing where it was observed that the model would trim by the bow, and thus raise the transom. It was also felt that owing to the low B/H value of 1.5, the bulb

was too far below the surface of the water. The model was trimmed 0.75 inches by the stern which corresponds to 3 ft. on the full size ship.

The resulting R_t/v^2 curve (Fig. B-3) starts out the same as the zero trim case, but then increases the hump at $V/\sqrt{L} = 0.9$. At $V/\sqrt{L} = 0.95$ it goes below the zero trim condition and remains there for the balance of the speed range. The percentage improvement on the total ship resistance is 2% at $V/\sqrt{L} = 1.2$ and 3.5% at $V/\sqrt{L} = 1.3$. The reasons for this improvement can be attributed to the following:

1) The bulbous bow is closer to the surface

2) The longitudinal center of buoyancy (LCB) shifted from 1.2% of L aft of ⊗ to 2.65% of L aft of ⊗ .

3) The prismatic coefficient increased to .611, which is in line with using a larger Cp at higher speeds.

4) The transom immersion was increased by approximately 1.2 ft. full scale.

5) There was negligible change in the wetted surface.

Using reasoning similar to that applied in the reflection theory analysis, a method of getting resistance values for a catamaran by towing only a single hull was investigated. The imaginary centerline plane previously mentioned was replaced by a thin, flat plate with faired ends which was towed off tank centerline a distance corresponding to one half the hull separation and rigidly connected to the towing

carriage. The model was towed on centerline and connected to the dynomometer. (See Appendix E for test set up) The dimensions of the plate area 5 ft. x 1 ft. x 3/16 in. thick. It was towed 9 inches off centerline, which corresponds to the 18 inch separation, at a draft of 8 inches, which was greater than the 6.4 inches for the model. As the model is 4 ft. long the plate extended 6 inches fore and aft in the longitudinal direction. The resulting R_t/v^2 values were doubled and plotted on the same curve for Q= 18" (Fig. B-3).

The resulting plot duplicated the shape of the original curve with regard to humps and hollows. The percentage difference ranged from a 3% to 5% increase. This difference, since it is relatively constant, could be applied to the model results in way of a correction factor to simulate the twin hull results. If the data were expanded without correction it would have a greater increase on residuary resistance and would not be representative. This is more important at the lower speeds where the frictional resistance is large in comparison to the total resistance because these small differences in model results represent a considerable percentage variation in residuary resistance.

Based on these results future work in this area looks promising and since the twin hull resistance plots are

available, all separations could be considered to assess whether applying a correction factor is reasonable. It is also recommended that a larger plate be used, its draft being about 2 ft., which corresponds to 1/2 the model length or 1/2 the wave length, and its length being about 6 ft., which is 1.5 times the model length. This combination may possibly give better results.

The value of this method of testing can be easily realized in that only one model need be constructed, plus the fact that existing models could be evaluated as to their performance as catamarans.

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APPENDIX A

FORMULAE AND SYMBOLS

C_f Frictional-resistance coefficient, $\dfrac{R_f}{\frac{\rho}{2} S v^2}$

where v is in ft-sec

C_r Residual-resistance coefficient, $\dfrac{R_r}{\frac{\rho}{2} S v^2}$

C_t Total-resistance coefficient, $\dfrac{R_t}{\frac{\rho}{2} S v^2}$

Ⓒ Total-resistance coefficient (circle coefficient system), $\dfrac{1000}{8\pi} \cdot \dfrac{S}{\nabla^{2/3}} \cdot C_t$

Ⓚ Speed coefficient (circle coefficient system), $\dfrac{v}{\nabla^{1/6}} \sqrt{\dfrac{4\pi}{g}}$

where v is in ft/sec

EHP Effective horsepower,

$$\frac{C_t \cdot \frac{\rho}{2} S v^3}{550 \text{ ft-lb/sec}} = \frac{R_t\, v}{550}$$

where v is in ft/sec

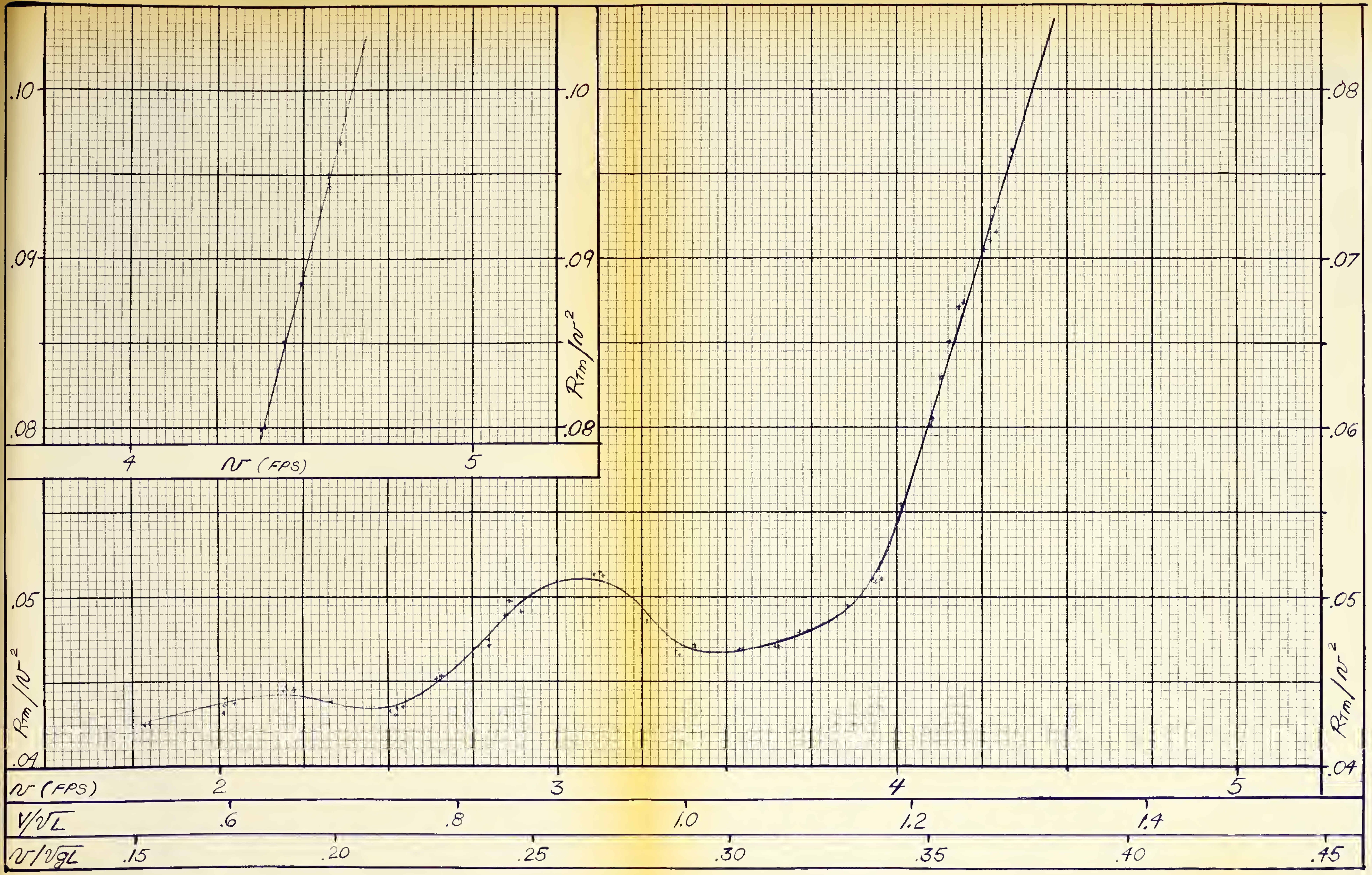
R_e Reynold's number, $\dfrac{vL}{\nu}$

where v is in ft/sec
L = L.W.L.

R_f	Frictional resistance in lbs.
R_r	Residual resistance in lbs.
R_t	Total resistance in lbs.
S	Wetted surface in sq. ft.
v , V	Speed in ft/sec or knots, respectively
$v / \sqrt{gL}$	Froude number, where v is in ft / sec, L = L.B.P.
$V / \sqrt{L}$	Speed-length ratio, where V is in knots, L = L.B.P.
Δ	Tons of displacement in salt water
∇	Immersed volume in cu. ft.
ρ	Density of water in $lb\text{-}sec^2/ft^4$
ν	Kinematic viscosity of water in ft^2/sec

APPENDIX B

RESULTS OF TESTING



NOTES:

① R_{Tm} = TOTAL MODEL RESISTANCE, LBS.

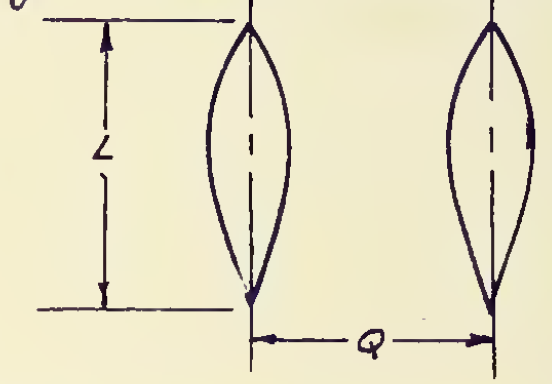
$\mathcal{N}$ = MODEL SPEED, FT/SEC

V = MODEL SPEED, KNOTS

L = MODEL LENGTH, (LBP) FT

Q = MODEL SEPARATION, ℄ TO ℄, IN.

g = GRAVITATIONAL CONSTANT = 32.2 FT/SEC²



② TURBULENCE STIMULATION:
1/8" D. X .035" PINS ON 1/4" CTRS
LOCATED 4" AFT OF F.P.

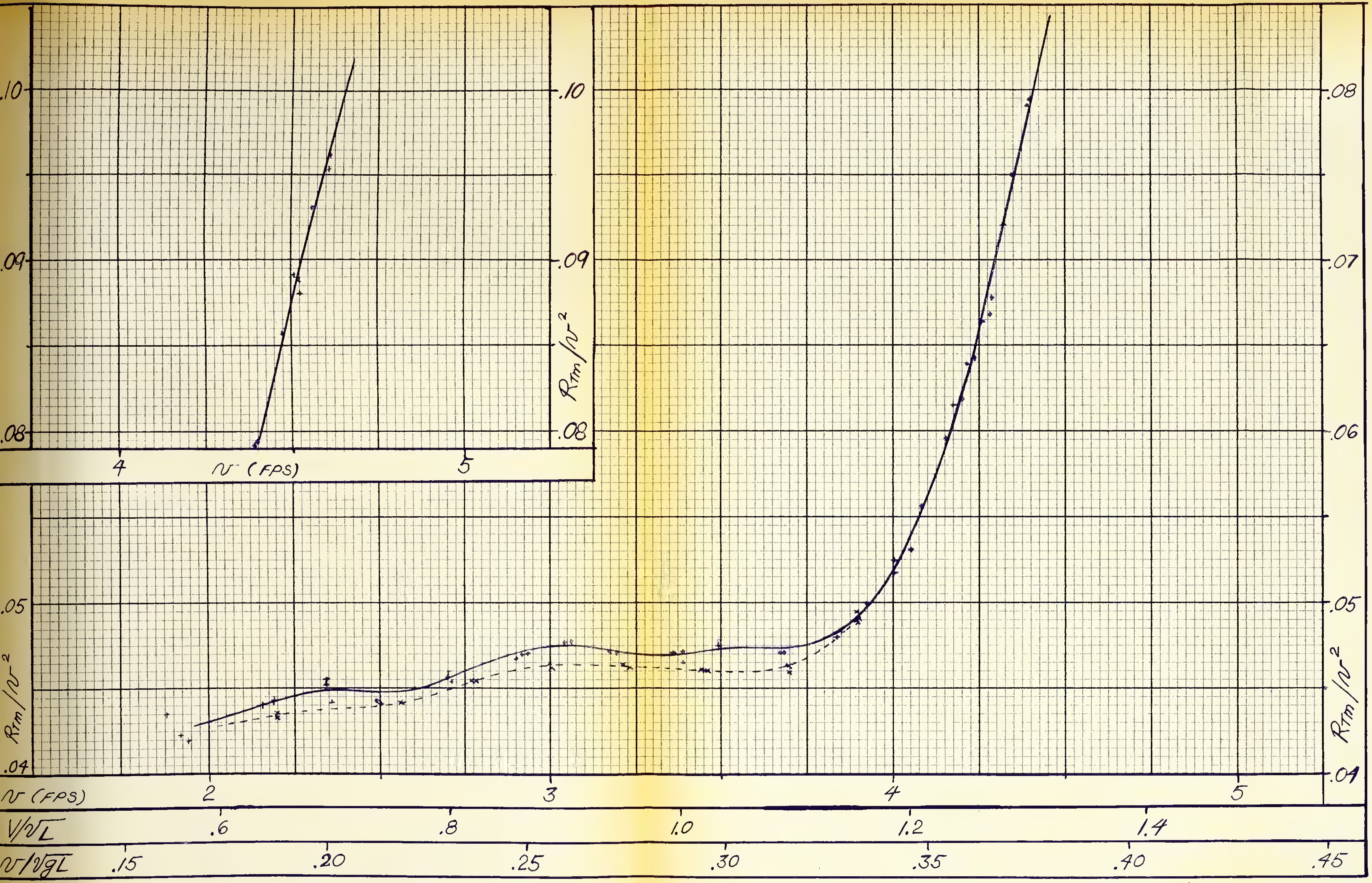
③ $Q/L = .250$
$Q/B = 1.87$

FIG. B-1

RESULTS OF TESTING
18 MARCH - 15 APRIL 1967

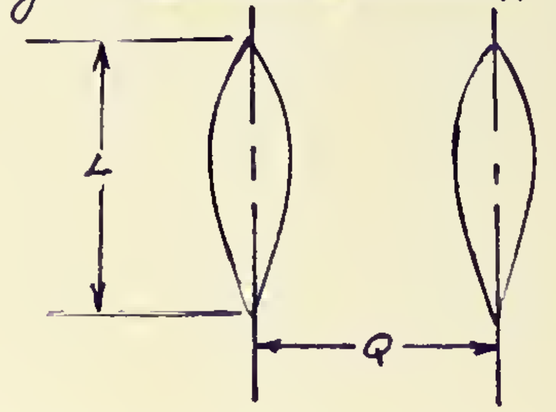
WATER TEMPERATURE = 80°F

WC-1 Q = 12 IN.



NOTES:

① R_{Tm} = TOTAL MODEL RESISTANCE, LBS.
$\mathcal{V}$ = MODEL SPEED, FT/SEC.
V = MODEL SPEED, KNOTS.
L = MODEL LENGTH, FT. (LBP)
Q = MODEL SEPARATION, ℄ TO ℄, IN.
g = GRAVITATIONAL CONSTANT = 32.2 FT/SEC²

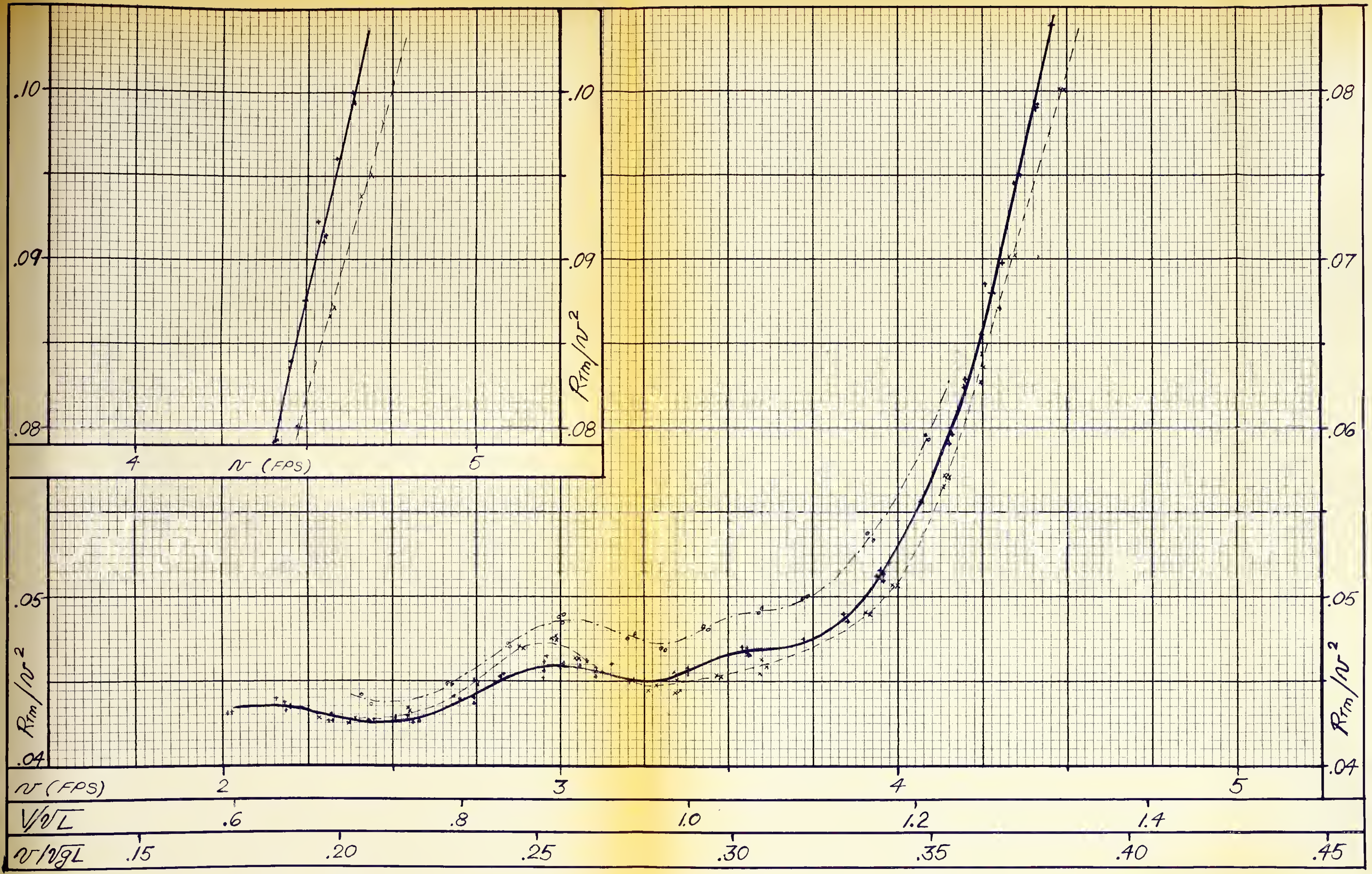


② TURBULENCE STIMULATION
+——+——+ D=.125 IN X .036 IN PINS ON 1/4" CTRS. LOCATED 1" AFT OF F.P.
x- - -x- - -x ALTERNATE SMALL & LARGE PINS ON 3/8" CTRS.
SMALL PINS D=.125" X .035 IN HIGH
LARGE PINS D = 1/4", H = 1/16"

③ Q/L = .3125
Q/B = 2.34

FIG. B-2

RESULTS OF TESTING
24 MARCH – 18 APRIL 1967
WATER TEMPERATURE = 80°F
WC-1   Q = 15 IN.



NOTES:

① R_{Tm} = TOTAL MODEL RESISTANCE, LBS

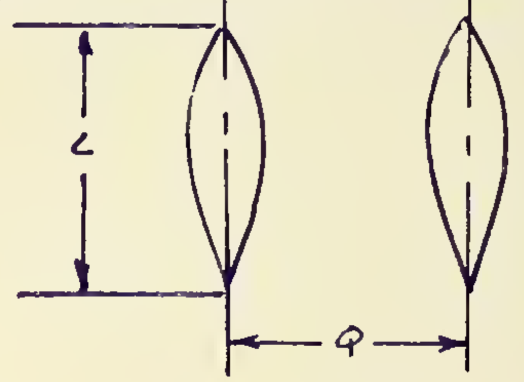
v = MODEL SPEED FT/SEC.

V = MODEL SPEED, KNOTS

L = MODEL LENGTH, FT (LBP)

Q = MODEL SEPARATION, ℄ TO ℄, IN

g = GRAVITATIONAL CONSTANT = 32.2 FT/SEC²



② TURBULENCE STIMULATION: 1/8" D x .035" PINS ON 1/4" CTRS LOCATED 9" AFT OF F.P.

③ Q/L = .375

Q/B = 2.81

④ LEGEND

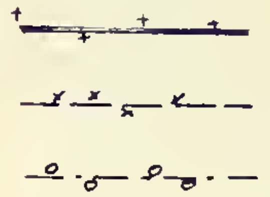
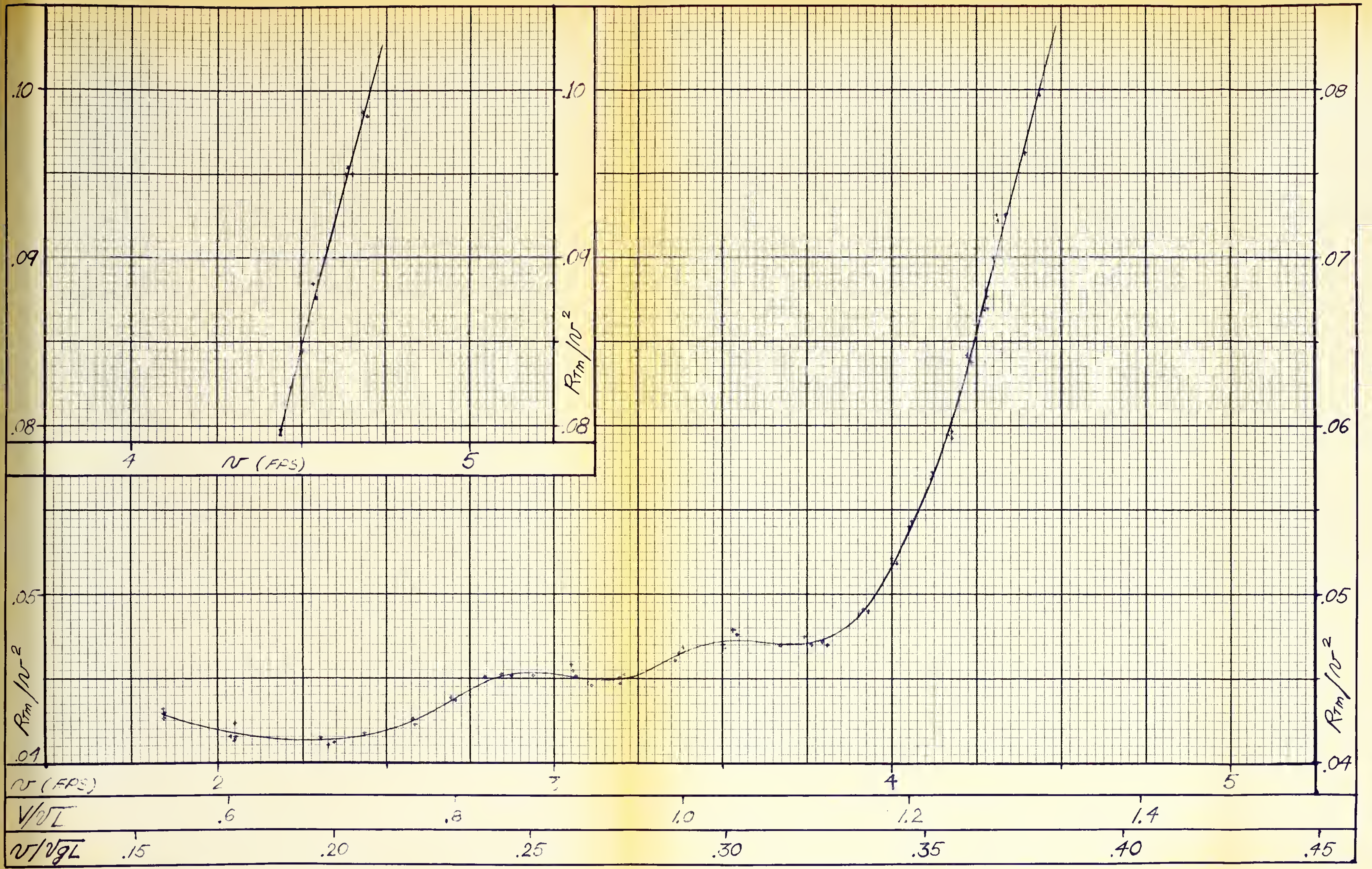


FIG. B-3

RESULTS OF TESTING
25 MARCH - 8 APRIL 1967
WATER TEMPERATURE = 80°F
WC-1 Q = 18 IN.



NOTES:

① R_{Tm} = TOTAL MODEL RESISTANCE, LBS.

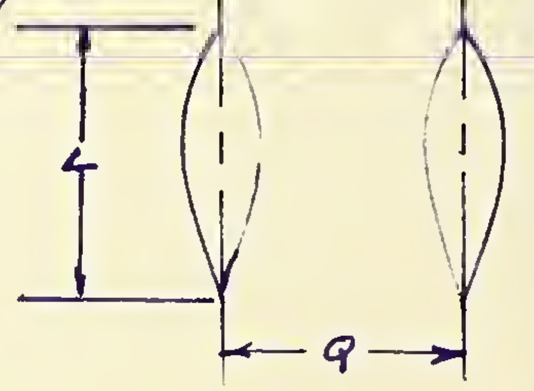
$\mathcal{V}$ = MODEL SPEED, FT/SEC.

V = MODEL SPEED, KNOTS.

L = MODEL LENGTH (LBP), FT.

Q = MODEL SEPARATION, ℄ TO ℄, IN.

g = GRAVITATIONAL CONSTANT = 32.2 FT/SEC²



② TURBULENCE STIMULATION:
1/8" D. X .035" PINS ON 1/4" CTRS.
LOCATED 4" AFT OF FP

③ $Q/L = .4375$

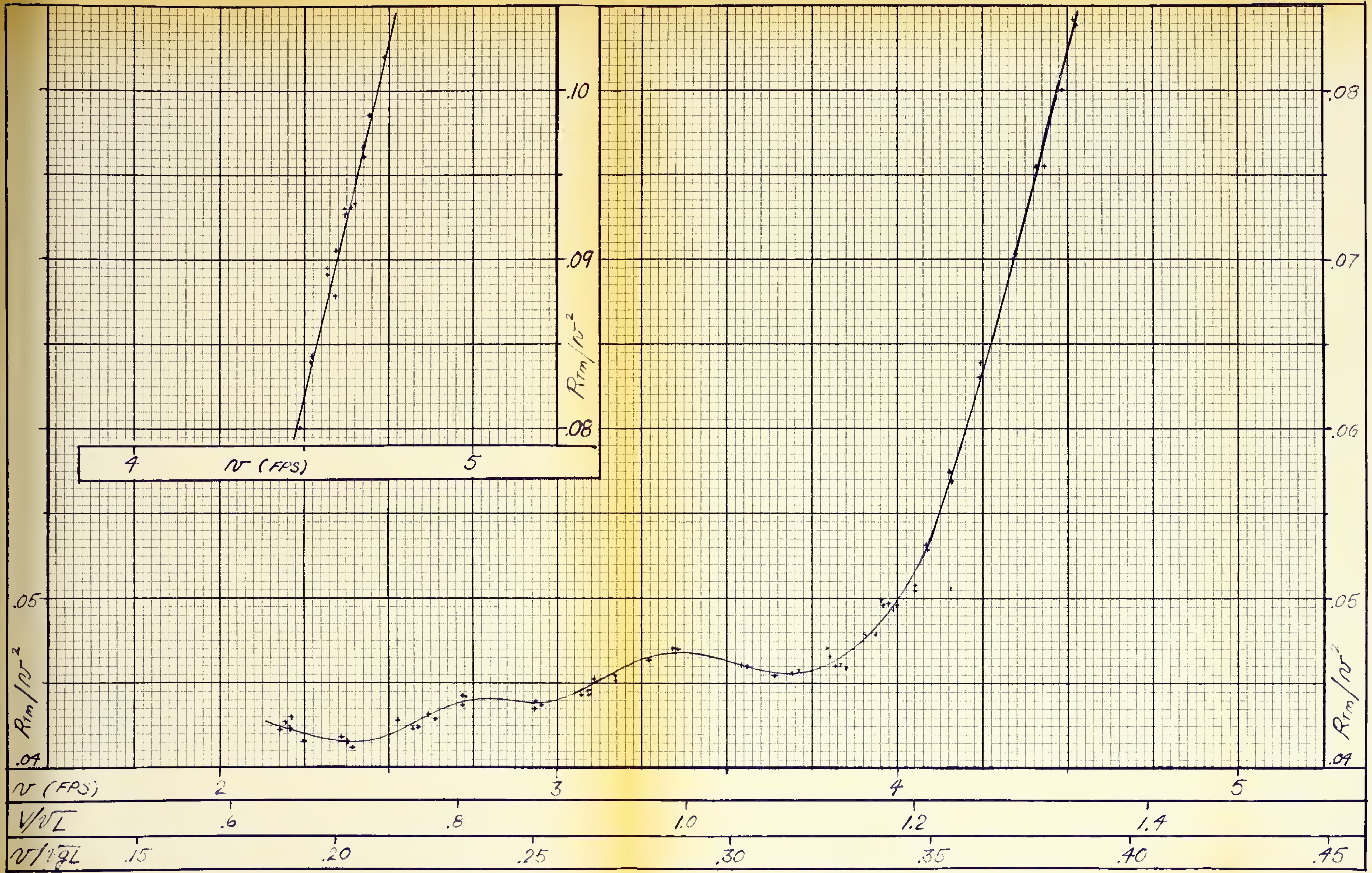
$Q/B = 3.26$

FIG. B-4

RESULTS OF TESTING
25 MARCH - 8 APRIL 1967

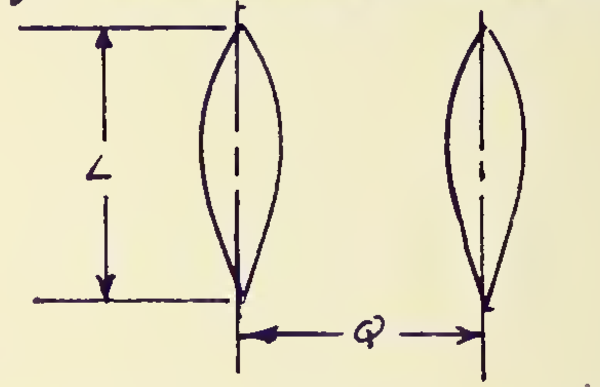
WATER TEMPERATURE = 80°F

WC-1 Q = 21 IN.



NOTES:

① R_{Tm} = TOTAL MODEL RESISTANCE, LBS.
v = MODEL SPEED, FT/SEC.
V = MODEL SPEED, KNOTS
L = MODEL LENGTH, FT (LBP)
Q = MODEL SEPARATION, ℄ TO ℄, IN.
g = GRAVITATIONAL CONSTANT = 32.2 FT/SEC²

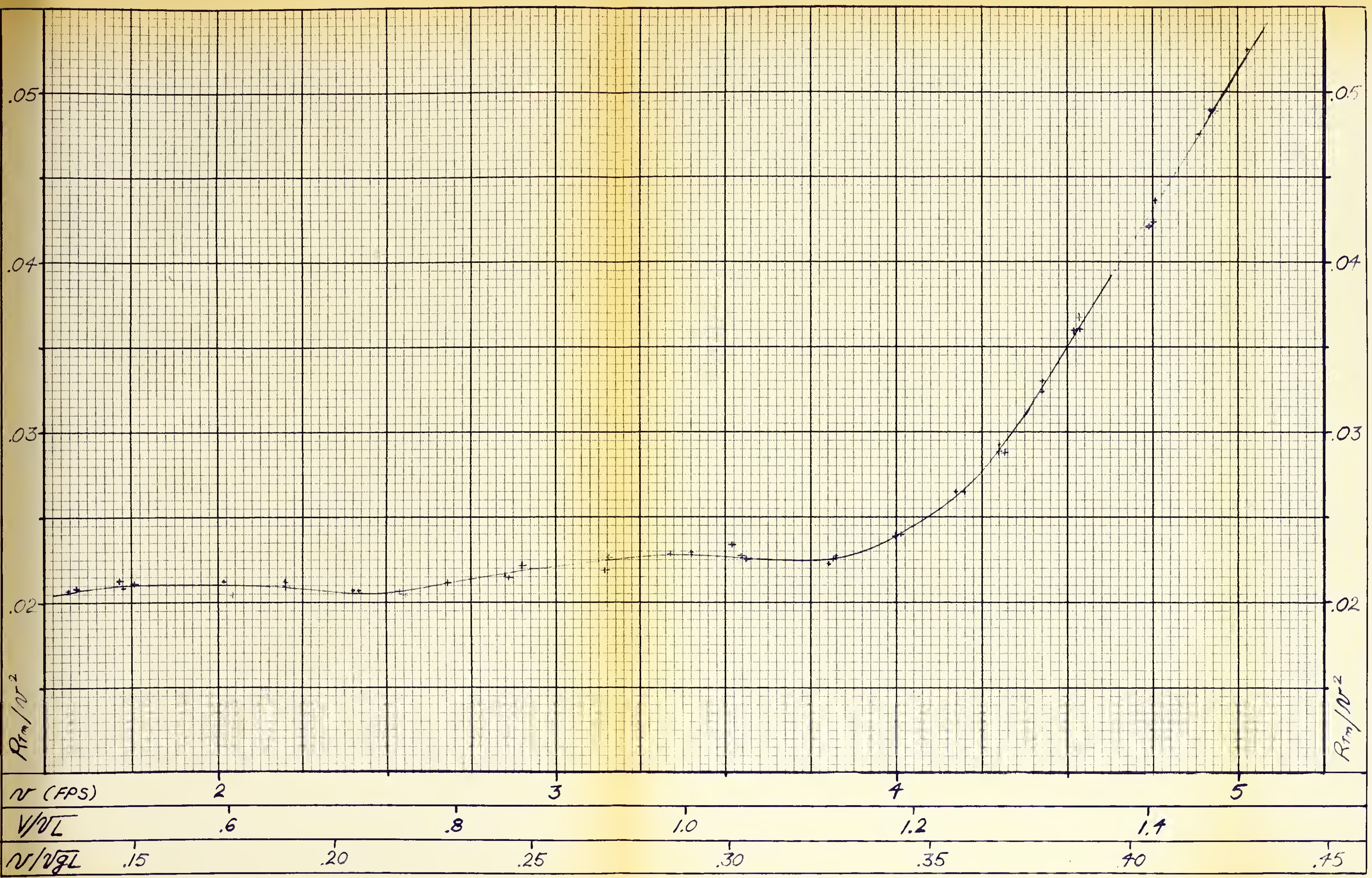


② TURBULENCE STIMULATION:
1/8" D. X .035" PINS ON 1/4" CTRS.
LOCATED 4" AFT OF F.P.

③ Q/L = .500
Q/B = 3.74

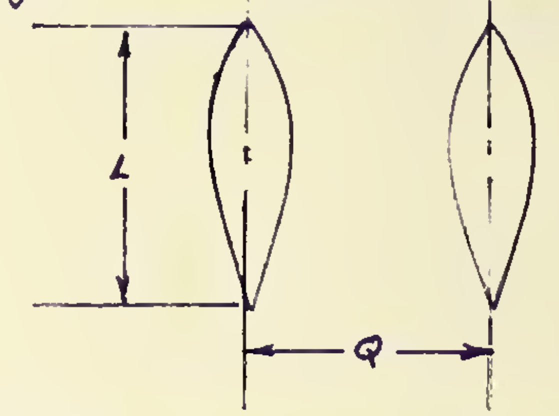
FIG. B-5

RESULTS OF TESTING
28 MARCH – 6 APRIL 1967
WATER TEMPERATURE = 80°F
WC-1 Q = 24 IN.



NOTES:

① R_{Tm} = TOTAL MODEL RESISTANCE, LBS.
v = MODEL SPEED, FT/SEC
V = MODEL SPEED, KNOTS.
L = MODEL LENGTH, FT.(LBP)
Q = MODEL SEPARATION, ℄ TO ℄, IN
g = GRAVITATIONAL CONSTANT = 32.2 FT/SEC.



② TURBULENCE STIMULATION:
D=.125 X .055 IN PINS ON 1/4" CTRS.
LOCATED 9" AFT OF F.P.

③ INFINITE SEPARATION SIMULATED BY SINGLE HULL TEST.

FIG. B-6

RESULTS OF TESTING
30 MARCH - 1 APRIL, 1967
WATER TEMPERATURE = 80° F
WC-1 Q = ∞

APPENDIX C

SAMPLE CALCULATIONS

The following is an example of the computational procedure followed in expanding model resistance to full-scale ship resistance. The calculations are for Q = 24 in.

Blockage Correction:

$v = 3.0$ ft/sec $\qquad R_t/v^2 = 0.0443$

$1.004\ v = 3.012$ ft/sec $\qquad 0.9921 R_t/v^2 = 0.0439$

See Section on Blockage Correction.

Expansion to Full Ship Size:

$v = 3.012$ ft/sec

$$V_s = \frac{V_m\sqrt{L_s}}{\sqrt{L_m}} = \frac{v_m\sqrt{L_s}}{1.689\sqrt{L_m}} = \frac{(14.13)\ (3.012)}{(1.689)\ (2.0)} = 12.599 \text{ kts.}$$

$$v_s = 1.689 V_s = (1.689)\ (12.599) = 21.280 \text{ ft/sec}$$

$$v_s^2 = 452.84$$

$$R_{e_s} = \frac{v_s\ L_s}{\nu} \qquad \nu = 1.2817 \times 10^{-5} \text{ @ } 59^\circ\text{F (SW)}$$

$$R_{e_s} = \frac{(21.280)\ (200)}{(1.2817 \times 10^{-5})} = 3.321 \times 10^8$$

$$C_{f_s} \text{ (ITTC)} = 1.764 \times 10^{-3}$$

$$\Delta C_{f_s} = 0.400 \times 10^{-3}$$

$$C_{f_s} + \Delta C_{f_s} = 2.164 \times 10^{-3}$$

R_{t_m}/v_m^2 (From Model Resistance Curve) = .0439

$$R_{e_m} = \frac{v_m L_m}{\nu} \qquad \nu = 0.92969 \times 10^{-5} \text{ @ } 80^\circ F \text{ (FW)}$$

$$R_{e_m} = \frac{(3.012)\ (4.0)}{(.92969 \times 10^{-5})} = 1.2959 \times 10^{6}$$

$$C_{f_m} \text{ (ITTC)} = 4.434 \times 10^{-3}$$

$$C_{t_m} = \frac{R_{t_m}}{v_m^2\ \frac{\rho}{2}\ S_m} = \frac{(.0439)}{(.9668)\ (984)} = 6.646 \times 10^{-3}$$

$$\frac{\rho}{2} = 0.9668 \text{ @ } 80^\circ F \text{ (FW)}$$

$$S_m = 984$$

$$C_{r_m} = C_{r_s} = C_{t_m} - C_{f_m} = 6.646 - 4.434 = 2.212 \times 10^{-3}$$

$$C_{t_s} = C_{f_s} + \Delta C_{f_s} + C_{r_s} = 2.164 + 2.212 = 4.376 \times 10^{-3}$$

$$R_{t_s} = C_{t_s}\ \frac{\rho}{2}\ S_s\ v_s^2 \qquad \frac{\rho}{2} = .9925 \text{ @ } 59^\circ F \text{ (SW)}$$

$$S_s = 16{,}918$$

$$R_{t_s} = (4.376 \times 10^{-3})\ (.9925)\ (16{,}918)\ (452.84)$$

$$R_{t_s} = 33{,}274$$

$$EHP = \frac{R_{t_s} \cdot v_s}{550} = \frac{(33{,}274)\ (21.28)}{550} = 1287$$

Calculation of Ⓒ

$v_m = 3.012 \quad v_s = 21.28$

$C_{t_s} = 4.376 \times 10^{-3}$

$$Ⓒ = \frac{1000}{8\pi} \cdot \frac{S}{\nabla^{2/3}} \cdot C_{t_s} = 254 \; C_{t_s}$$

$$Ⓒ = 4.376 \times 10^{-3} \times 254 = 1.112$$

Calculation of Ⓚ

$v_m = 3.012 \quad v_s = 21.28$

$$Ⓚ = \frac{v_s}{\nabla^{1/6}} \sqrt{\frac{4\pi}{g}} = 0.0919 \; v_s$$

$$Ⓚ = 0.0919 \times 21.28 = 1.956$$

APPENDIX D

BLOCKAGE CORRECTION

By using the results of shallow water channel tests (15), one can correct the resistance of large models tested at the Robinson Model Basin to agree with the open water or the unrestricted channel resistance. The controlling parameters for this correction are:

v = speed of model (ft/sec)

v_∞ = speed in an unrestricted channel at which the resistance is the same as for speed v in a restricted channel (ft/sec)

A_x = midship section area (ft^2)

w = width of channel (ft)

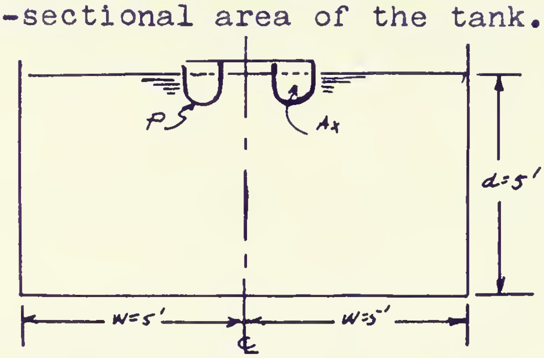
d = depth of channel (ft)

p = girth of model at maximum section (ft)

r = hydraulic radius

v_a = Schlicting's intermediate speed (ft/sec)

For WC-1 it was assumed that each hull occupied one-half the cross-sectional area of the tank.



The hydraulic radius is given as:

$$r = \frac{2(wd - A_x)}{w + 2d + p} = \frac{2(5x5 - .164)}{5 + 10 + 1.08} = 3.089$$

Examination of Fig. 9 (15) shows that the depth correction for speed (v_a/v_∞) which was taken from Schlichting's shallow water resistance predictions is equal to 1 for $\frac{v_\infty}{\sqrt{gd}} < 0.5$ This corresponds to an unrestricted channel speed of $v = (\sqrt{gd})(.5) = \sqrt{(32.2)}(.5) = 6.36$ ft/sec, which is well in excess of the maximum speed employed. This essentially means that the depth of the tank is sufficient and affords no increase in resistance due to shallow water.

Since there is no depth correction, $v_a = v_\infty$, therefore, the balance of the correction is a function of the overall tank restriction.

For $2\sqrt{A_x}/r = 2\sqrt{.1639}/3.089 = .272$ from Fig. 9 (15), for restricted channel data, $v/v_a = .996$.

Since $v_a = v_\infty$, $v/v_\infty = .996$ and $v = .996\ v_\infty$

In other words, the speed in the tank corresponds to 99.6% of the unrestricted channel speed.

Results of model tests are plotted in terms of R_t/v^2 vs. v.

$$\frac{R_t}{v^2}\text{ (restricted channel)} = \frac{R_t}{v_\infty^2}\text{ (open water)} = \frac{R_t}{(v+\Delta v)^2}$$

But $v_\infty = 1.004\ v$, therefore, $(v+\Delta v) = (v + .004v)$

and, $(v+\Delta v)^2 = (v^2 + 2(\Delta v)v + \Delta v^2)$

$$\Delta v^2 \text{ approx.} = 0$$

thus, $(v+\Delta v)^2 = v^2 + 2(\Delta v)v = v^2 + 2(.004)v^2 = 1.008v^2$

Now, $$\frac{R_t}{v^2}\text{ (restricted channel)} = \frac{R_t}{v^2(1.008)}\text{ (open water)}$$

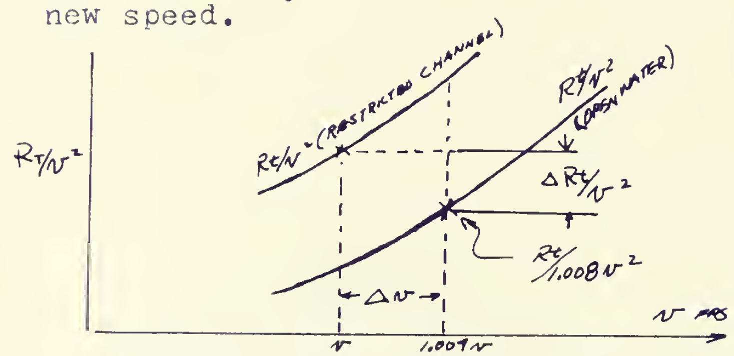
The correction is made as follows:

1) For a given speed read the corresponding R_t/v^2 value as plotted.

2) Correct the speed to open water speed, i.e., $V_{new} = 1.004\ v_{initial}$

3) Correct the R_t/v^2 value by dividing by 1.008.

4) This lower R_t/v^2 value is then plotted at the new speed.



As the blockage correction was small (1% - 3%) it was decided not to plot the corrected curve but to include the correction in the expansion. Thus, for a given speed the R_t/v^2 value was read, the speed and R_t/v^2 values were then corrected and the expansion carried on as indicated in the sample calculations (Table V).

APPENDIX E

PHOTOGRAPHS